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Survey of the Keewatin Uranium Mineralization Areas with Respect to Natural Occurrence of Radionuclides in Vegetation, Soils and Sediments

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Northern Affairs Program

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PREFACE

The objective of this monograph was to summarize in a comprehensive way the results of a two year (1981,1982) intensive survey of naturally occurring radionuclides in vegetation and various substrates in Central Keewatin, N.W.T.

The monograph is based largely on the M.Sc. thesis of T.T. Lei: "Burden and distribution of uranium radionuclides and fallout ^{137}Cs in Central Keewatin, N.W.T.", (Department of Botany, University of Toronto, 1984). Copies of the thesis are available in the DINA central library in Ottawa, in the regional library in Yellowknife or from the Department of Botany, University of Toronto.

ACKNOWLEDGEMENTS

The logistic support and helpful cooperation by Dr. Martin Barnett and Dr. Larry Burgess of ALUR are gratefully acknowledged. Our gratitude goes to Dr. Al Miller of the Geological Survey of Canada for his suggestions of uranium mineralization sites amenable to this study. Dr. Kaye McInnes, Joan Scottie and Dr. Pierre Laporte from the Department of Indian and Northern Affairs gave valuable help in the field when it was most needed.

The kindness shown by the employees of Urangesellschaft Canada Ltd. is greatly appreciated. The Company has provided helicopter support and lodging for our party during the two field seasons. Dr. Wolfgang Hilger was most cooperative and Vice-president Mike Stewart, Dr. Egfried Prosser, Don Speller, High Ikoe and Stanley Zezelnichuk also contributed to our pleasant and productive stay at Lone Gull Camp in 1981 and 1982.

The Nogash Camp geologists, Dr. Dave Reid and Dr. Robbin Chisholm of Pan Ocean Oil Ltd., were helpful in providing helicopter time and lodging in 1981.

ABSTRACT

The plants and substrates of the central District of Keewatin, N.W.T. Canada were studied for their content of uranium family radionuclides (^{238}U and ^{226}Ra) and fallout ^{137}Cs.

Two sites, Lone Gull (64°20'N, 97°30'w) Nogash (62°35'N, 98°30'W) with significant uranium mineralization were studied intensively. Transects over 1 km long intercepting the mineralization zones were chosen to determine the lateral distribution of uranium radionuclides in vegetation, peat and mineral substrate.

Twenty-one sites within an area of 10,000 km^2 were also investigated during the summers of 1981 and 1982. Known uranium mineralization areas were present in thirteen of these sites; the other eight were chosen arbitrarily with no previous knowledge of their mineral conditions. The aim of this extensive search was to compile an inventory of the natural levels of the radionuclides mentioned above in the tundra surface, within the region of Keewatin, N.W.T. in anticipation of future mining activities.

The background level of ^{238}U in plants was ca. 0.5 ppm, reaching 16,000 ppm in the mosses found near the radioactive frost boils at Lone Gull. The average concentration in the substrate was ca. 1 ppm except at the most radioactive sites where 23,000 ppm were measured in the mineral substrate.

^{226}Ra concentrations in the plants were low in the non-mineralized sites, usually below the detection limit of the Ge(Li) counting system of 1 pCi/g. The highest value was recorded in the sedges at the Lone Gull main showing area at 933 pCi/g. The background level in the substrate was found to be 1.5 pCi/g.

The levels of the fallout product, ^{137}Cs in the plants and the substrates were very consistent throughout the study area. There were 8 pCi/g of ^{137}Cs in the composite vegetation and 2 pCi/g in the substrate.

At Lone Gull, the lateral distribution of ^{238}U and ^{226}Ra was highly source-dependent in that anomalous levels were detected only within ca. 100 m radius of the radioactive outcrop. However, higher ^{238}U and ^{226}Ra activities were detected in the drainage basin up to 600 m south of the main showing. ^{238}U and ^{226}Ra tended to be evenly distributed through the soil profile. ^{137}Cs, on the other hand, was strongly associated with the top 5 cm of the substrate.

Habitat conditions and edaphic factors were examined in relation to the pattern of distribution for these radionuclides.

Individual species were evaluated for their ^{238}U and ^{226}Ra content in an attempt to discover indicators for the occurrence of uranium mineralization.

RÉSUMÉ

Étude des terrains uranifères du Keewatin : présence naturelle de radionucléides dans la végétation, le sol et les sédiments

par

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RÉSUMÉ

Les végétaux et les sols de la zone centrale du district de Keewatin (T. N.-O.), au Canada, ont fait l'objet d'études pour connaître leur teneur en radionucléides de la famille de l'uranium (^{238}U et ^{226}Ra) et pour les retombées de ^{137}Cs.

Deux secteurs, Lone Gull (64° 20' N. et 97° 30' W.), et Nogash (62° 35' N. et 98° 30' W.), à fortes teneurs en minerai d'uranium, ont fait l'objet de recherches poussées. Des sections transversales de plus de 1 km de long, interceptant les zones de minéralisation, furent tracées pour déterminer la répartition latérale des radionucléides d'uranium dans la végétation, la tourbe et la couche minérale.

De plus, vingt-et-un sites furent examinés dans une région de 10 000 km^2 pendant les étés de 1981 et de 1982. Il y avait des zones de minéralisation d'uranium connues dans treize de ces sites; les huit autres furent choisis arbitrairement sans connaissance préalable de leurs caractéristiques minérales. Le but de ces recherches était de dresser un inventaire de concentrations naturelles des radionucléides mentionnés ci-dessus, à la surface de la toundra, dans le district de Keewatin (T. N.-O.), en vue de futures activités d'exploitation minière.

La concentration naturelle de ^{238}U chez les plantes était d'environ 0,5 ppm, atteignant 16 000 ppm dans les mousses poussant près des bosses de gel radioactives à Lone Gull. La concentration moyenne du sol était d'environ 1 ppm, excepté aux sites les plus radioactifs où 23 000 ppm furent mesurées dans la couche minérale.

Les concentrations de ^{226}Ra chez les plantes étaient faibles dans les sites non minéralisés, habituellement en-dessous de la limite de détection du système de comptage Ge(Li), soit 1 pCi/g. La valeur maximale fut mesurée dans le carex du principal affleurement à Lone Gull, soit 933 pCi/g. La concentration naturelle de la couche minérale était de 1,5 pCi/g.

Les concentrations des retombées de ^{137}Cs chez les plantes et dans le sol étaient assez homogènes dans toute la zone étudiée. Il y avait 8 pCi/g de ^{137}Cs dans la végétation mixte, et 2 pCi/g dans le sol.

A Lone Gull, la répartition latérale de ^{238}U et de ^{226}Ra était étroitement liée à la distance de la source; en effet, des niveaux anormaux n'ont été décelés que dans un rayon d'à peu près 100 m de l'affleurement radioactif. Mais, des concentrations plus fortes de ^{238}U et de ^{226}Ra furent décelées dans le bassin hydrographique, jusqu'à 600 m au sud de l'affleurement principal. ^{238}U et ^{226}Ra semblaient être répartis uniformément dans le profil du sol. Par contre, ^{137}Cs se retrouvait plutôt dans la couche supérieure de 5 cm d'épaisseur.

Les conditions de l'habitat et les facteurs édaphiques furent étudiés selon la répartition de ces radionucléides.

Des espèces furent évaluées individuellement pour leur teneur en ^{238}U et en ^{226}Ra, afin de découvrir des indicateurs de la présence d'uranium.

INTRODUCTION

Canada has been and will be a major uranium producer for most of the coming century (OECD 1982). As a consequence we can expect further extensive uranium exploration in Canada and an increased accumulation of uranium mining and milling wastes in the future. The present study was initiated in anticipation of these activities which could potentially cause undesirable, if not, dangerous environmental contamination as an aftermath of uranium mining activities.

Definition of the Problem

There is growing concern about the consequences of the release of radionuclides, additional to those of the natural background, through the proposed mining of uranium in the Keewatin District, N.W.T. Awareness of the consequences which such a release from extracted and processed ore might have on the environment, including its inhabitants, makes it necessary to have a thorough study of the natural radiation levels in the area concerned prior to the beginning of mining operations. Additional studies of a scientific nature should be undertaken also after the basic inventory is completed, to determine which plants are most effective in storing radionuclides.

Objectives of the Study were:

1) to determine the natural levels of uranium radionuclides (^{238}U, ^{226}Ra and ^{214}Bi) and ^{137}Cs in plants and substrates at localities of uranium occurrence and at sites with no reported uranium occurrence in the District of Keewatin, NWT.

At the present time the paucity of data on the uranium radionuclide content in arctic plants and soils makes it difficult to assess the implications of exposed uranium mineralizations on the tundra environment. Through the analyses of samples collected from both mineralized and 'background' localities, a baseline radionuclide load can be established. The radionuclide inventory may also allow for future comparisons in areas which may become disturbed by mining and milling activities.

The radionuclide burden of individual plant species was also examined for their correlation to known uranium mineralization. The possibility of using plants and substrates as means of uranium exploration is considered.

2) to determine the distribution of uranium radionuclides and ^{137}Cs laterally across uranium showings and vertically in the layers of plants, surface organic matter and the underlying mineral substrate. The involvement of ecological parameters such as plant cover, moisture regime and substrate characteristics on the radionuclide distribution is discussed.

3) to formulate recommendations concerning precautions to be observed in allocating sites for future tailing depositions associated with mining operations.

During the first phase of the project, which was conducted during the summer of 1981, we surveyed the vegetation and underlying substrate in the prospective uranium mineralization areas at Lone Gull (Urangesellschaft

Co.) and Nogash Camp (Pan Ocean Oil Co.) in the Keewatin District N.W.T. About 450 samples of plant, peat and soil material were collected and measured for their radionuclide content. The early results were summarized in the 1981 Progress Report to the director of ALUR.

During the second phase (summer 1982), the sampling at the Lone Gull and Nogash Camp sites was extended further from the centre of mineralization into the 'background' zone. In addition, an extensive sampling of 13 sites formerly explored for uranium and 9 arbitrary sites was conducted within the radius of 150 km from Baker Lake. This survey covered a variety of topographic, substrate and vegetation situations and produced adequate information about the peak and background levels of naturally occurring radioactivity in vegetation and upper layers of the substrate.

The inventory of natural radioactivity for the area will serve as a source of data to which future conditions created by mining activity may be compared. All samples have been retained in a depository for future possible analyses of heavy metals and other substances.

Uranium studies in the District of Keewatin have been carried out mainly by the GSC geologists and exploration companies. The GSC reports are easily obtainable and up-to-date, but the exploration reports of individual companies carry a 5-year delay in public release to protect the company's mining interests. In the Baker Lake area, the Lone Gull deposit has been thoroughly examined by Urangesellschaft Can. Ltd. (UG) since 1973. Since then, a substantial amount of information has been made public describing the geological, geophysical and geochemical conditions of the deposit. (Marmont et al. 1978; Bundrock 1981; Fuchs et al. 1982). There was, however, a lack of information on the pattern of natural radionuclide distribution in the active layer of the mineral substrate, the peat and the vegetation. It was an objective of the present study to address these particular aspects of the Lone Gull deposit.

One of the problems in geochemical prospecting is the establishment of the 'background' concentration of an element of concern. In a region where the effect of biotic and abiotic variables on mineral distribution are not well known or understood, this is of particular importance.

Uranium Family Radionuclide Distribution

^{226}Ra is one of the daughter nuclides in the ^{238}U family. This radionuclide is of environmental concern because of the presence of the prolific gamma-ray emitter ^{214}Bi. ^{238}U and ^{226}Ra behave differently in the surface environment. ^{238}U occurs mainly in two valency states: U^{+6} (commonly occurs in the form of the uranyl ion UO_2^{+2}) and U^{+4}. As UO_2^{+2} it is moderately mobile at pH < 4-8 and can be transported by water (Dunn and Ramaekers 1979). However, soluble uranium is easily scavenged by organic and clay particles. Under reduced conditions it is immobile. Radium is less mobile under oxidizing conditions which restricts its dispersion to a more confined region around the source. In an idealized dispersion model, the U/Ra ratio is lowest at the mineralized source and gradually increases with increasing distance from the source. In a reduced environment, ^{226}Ra has a mobility comparable to that of

uranium in an oxidized environment (Langmuir 1978; Rose et al. 1979). ^{214}Bi has a much shorter half-life ($T_{1/2}$=19.8 min) than its long-lived parent ^{226}Ra ($T_{1/2}$ = 1600 yr). It is therefore basically in secular equilibrium with ^{226}Ra through the intermediate isotope ^{222}Rn (radon) gas which is quickly dissipated in the environment.

The idealized dispersion model naturally excludes any ecological heterogeneity within the area of the dispersion halo. Topography, substrate characteristics, and vegetation cover significantly influence the meso- and micro-environment. It is important to consider the effect of these factors on the ideal model when we examine the dispersal patterns of uranium anomalies.

The long-lived fission products, ^{137}Cs and ^{90}Sr, generated during the atmospheric testing of nuclear weapons became a serious concern due to the associated hazard to human population and the ecosystem. Svoboda and Taylor (1979) and others have shown that 20 years after the signing of the moratorium on atmospheric testing in 1964, ^{137}Cs is still present in northern systems. Although the original deposition of fission products was higher in temperate regions than in the northern latitudes, ^{137}Cs is now highest in the midarctic tundra ecosystem especially in central Keewatin (Hutchison-Benson et al. 1985).

Since ^{137}Cs has been deposited as fallout, its pattern of distribution in the tundra environmnet would be more uniform and quite different from the localized occurrence of uranium radionuclides which originates in the substrate. In a local setting, this difference between the cesium and uranium radionuclide distribution may be used to demonstrate the migrational response of these two nuclide groups to ecological variables.

Radionuclides and Vegetation

In the realm of mineral exploration, the exploitation of a knowledge of the mineral content of plants and organic material in the substrate through chemical analysis is known as biogeochemistry (Brooks 1972). The basic assumption is that the uptake and retention of mineral elements in plants reflect the concentration of these elements in the substrate. Several uranium ore bodies were discovered through the chemical analysis of tree samples (Cannon 1960b). More recently, Dunn (1981,1982) has investigated the plant uptake of uranium in northern Saskatchewan where the major uranium reserves are located. He found uranium concentrations in ashed spruce twig and other boreal forest plants, growing at or near areas of uranium mineralization, were as much as 100 times that of the soil.

In geochemical and mineral exploration literature, geobotany is used to describe the response of plants to mineralized substrate in terms of appearance and distribution. Those species showing a strong positive correlation with a particular mineral are called indicators. Perhaps the most frequently-cited example of a uranium secondary indicator is the Astragalus species described by Helen Cannon (1957). The presence of these plants on the Colorado Plateau indicates high soil selenium which signals the presence of uranium mineralization. Although all the above examples are from non-permafrost regions, in the present study, the possibility of using biogeochemistry and geobotany as exploration tools in locating

uranium mineralization in the permafrost environment is examined.

Physical Environment of Central Keewatin

Geology. The study area belongs to the Churchill Structural Province of the Canadian Shield (Fig. 1a). The basement rocks are Archean granite gneisses and greenstones which were metamorphosed and intruded during the Kenoran Orogeny (2500 Ma [million years]). This complex was eroded and a series of Lower Proterozoic (Aphebian) shelf sediments was deposited. The subsequent Hudsonian Orogeny (1750-1850 Ma) deformed and metamorphosed the Lower Proterozoic sediments. Following this orogeny, a sequence of Middle Proterozoic (Helikian) sediments and volcanics of the Dubawnt Group was laid down. The Dubawnt Group lies unconformably (deposited over an older eroded rock stratum) over much of central Keewatin north and west of Baker Lake. A long period of erosion followed the Middle Dubawnt period and an extensive sequence of continental sandstones (Thelon Formation) was deposited. (Wright 1967; LeCheminant et al. 1980, Bundrock 1981; Fuchs et al. 1982).

Most of the mineralization occurrences in the study area are spatially related to the major Aphebian-Helikian unconformities. About half of the economical uranium reserves in Canada occur in deposits belonging to this geological setting (Ruzicka and Littlejohn 1982).

The Lone Gull uranium mineralization zone lies near the northeastern rim of a Helikian sandstone basin (Thelon Formation) that unconformably overlies Aphebian metasediments. At the main showing, uranium mineralization, within the Aphebian rocks, extends to more than 300 m in depth. Mineralization probably extended upward into the Thelon sandstone, but due to long-term erosion, only remnants of the mineralized sandstone are left at present.

The Nogash area is situated on Helikian Dubawnt Group sediments and volcanics that lie over similar older rocks as those at Lone Gull. The detailed information on the main uranium mineralization is not available. However, it appears to be associated with the hematite-alteration veins, some of which outcropped in this area embedded in basaltic extrusives.

Glacial History. During the period of Late Wisconsin Glaciation, the ice sheet advanced radially outward from the Keewatin Ice Divide (Fig. 1a). West of the Divide, the movement of ice was W and NW; east of the Divide, the movement was mostly SE. Glacial drift was the main deposit near the Keewatin Ice Divide (Cunningham and Shilts 1977).

Deglaciation occurred between 6000 and 8000 years ago. Large areas west of the Keewatin Ice Divide were inundated by proglacial lakes due to the damming effect of the retreating ice fronts. The maximum extent of proglacial lakes was 212-244 m above present sea level (a.s.l.). The disappearance of ice east of the Keewatin Ice Divide was followed by a 2000 year long marine inundation called the Tyrrell Sea (Lee 1960, Shilts 1972). This changed significantly the dispersal patterns of mineralization created by the movement of ice (Wright 1967; Marmont et al. 1976).

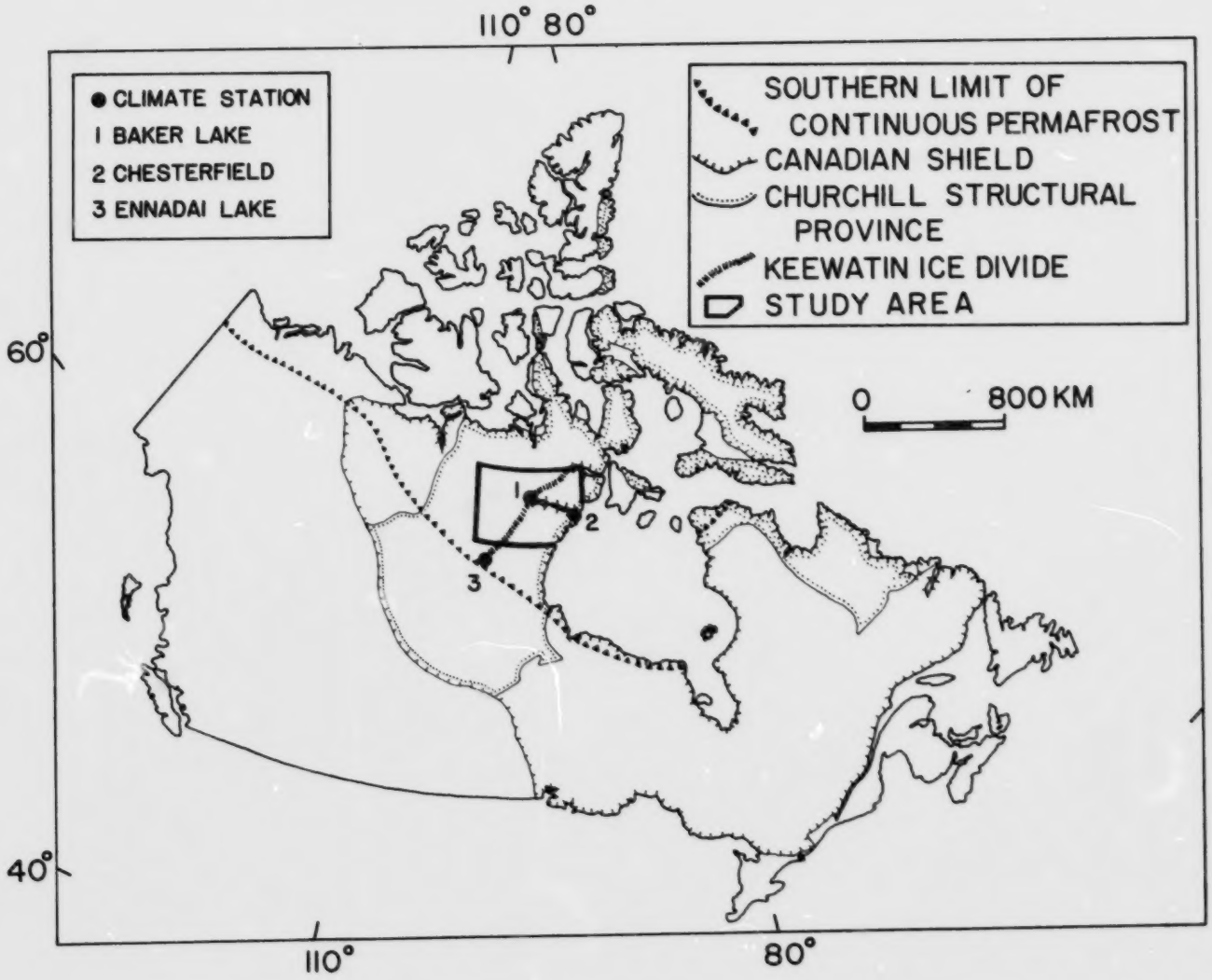

Fig. 1a Simplified map of Canada showing the study area.

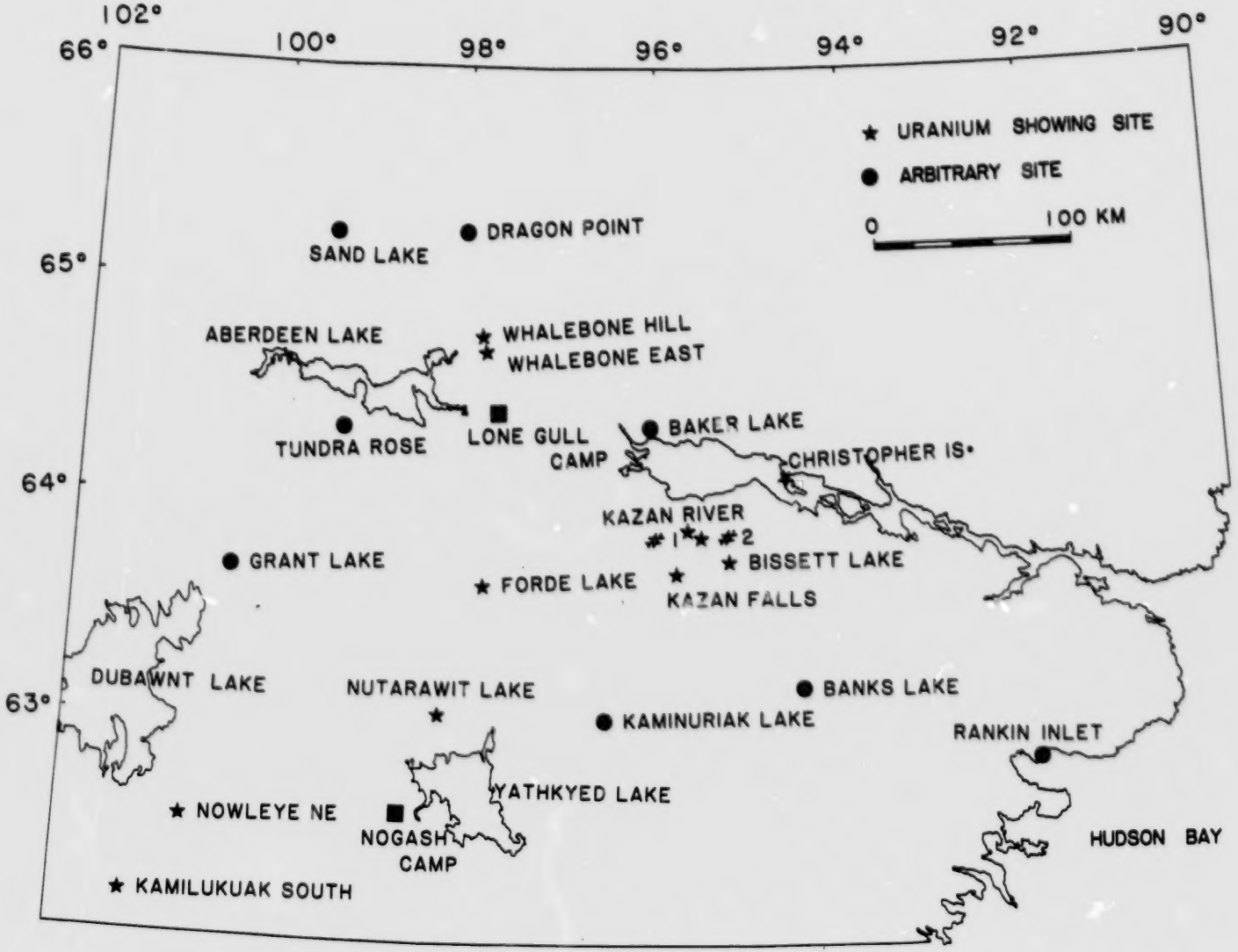

Fig. 1b Study area showing the intensive and extensive sampling sites and the Lone Gull and Nogash Camp sites.

Periglacial Environment. The study area lies within the Continuous Permafrost region (Fig. 1a). The active layer is 15-20 cm in low-lying, organic terrain and 150-200 cm in dry, sandy locations (Shilts 1977). A severe winter (-33°C in Jan.) and a cool summer (+13°C in July) characterize this region. The total annual precipitation is about 260 mm with an average of 110 days of precipitation. Spring melt begins in mid-June and lasts about 2 weeks during which time extensive flooding of the tundra occurs (Woo and Drake 1982). In Baker Lake, the average number of frost-free days is 78 (and 272 days of frost); the prevailing winds are from the N and NW (Nicholson 1976).

The soils in central Keewatin have been described as Dystric Brunisols (sandy upland) to Gleisolic Static Cryosols (wet depressions) (Zoltai and Johnson 1978). Organic material increases in the surface substrate towards the low-lying areas where a layer of undecomposed moss can reach to a depth of 15 cm. The mineral substrate frequently contains gravel to boulder-sized fractions, which belong to the underlying glacial drift which, in southern Keewatin, ranges in thickness between 0->30 m with an average of 3 m (Shilts 1977). Glacial overburden at Lone Gull Camp has been found to be 15-21 m (Hilger, 1984 personal communication).

The vegetation in the study area is typically low arctic with Lichen-Heath communities in the well-drained upland sites and extensive moss-sedge meadows in wet depressions. Low shrubs such as willows and dwarf birch are more abundant in wet-mesic areas. Scattered white spruce stands are present at Nogash Camp and Kamilukuak South.

PROCEDURES

Field Methods

Vegetation and substrate samples were collected from 21 sites widely spread over central Keewatin (13 sites are uranium "showing" sites and 8 were arbitrarily selected to represent the "background" condition) (Fig. 1b). The Lone Gull and Nogash notes were studied during July and August of 1981 and 1982 (Intensive Study Sites). The other 19 sites were studied in 1982 (Extensive Study Sites).

Intensive Study Sites. At the Lone Gull and Nogash sites a sampling scheme was designed to maximize the coverage of the showings and the surrounding environment, with due regard to the time and logistic limitations. At both camps, the existing prospecting grid system established by the exploration companies was used in the orientation of our sampling scheme.

At Lone Gull site (80 km west of Baker Lake; prospected by Urangesellschaft Canada Ltd.) sampling took place along two perpendicular transects (N-S and E-W) intercepting at the radioactive frost boils known as the Main Showing (Fig. 2a). Data were collected from a total of 86 sampling points.

Nogash site (240 km south of Lone Gull; exploration activities conducted by Pan Ocean Oil Ltd. and commencing 1982 by Aberford Resources Ltd.). Samples were collected along three transects perpendicular to and intercepting the mineralization zone (Fig. 2b). A total of 45 sampling points were investigated.

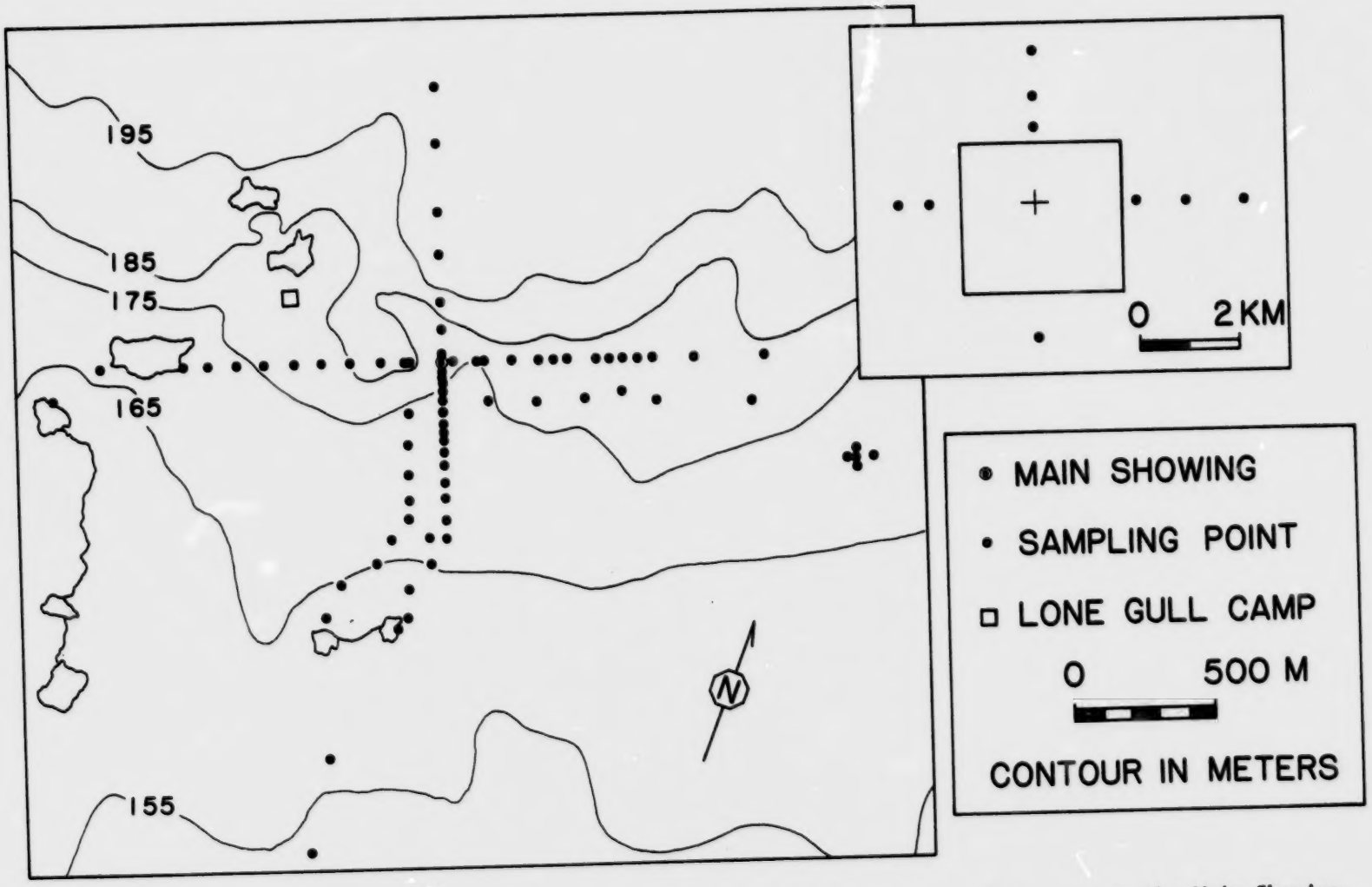

Fig. 2a Detailed sampling map of Lone Gull camp. The N-S and E-W transects intercept at the Main Showing. Sampling emphasis was placed on the area down-drainage from the mineralization. Inset indicates extended sampling points along the two main transects.

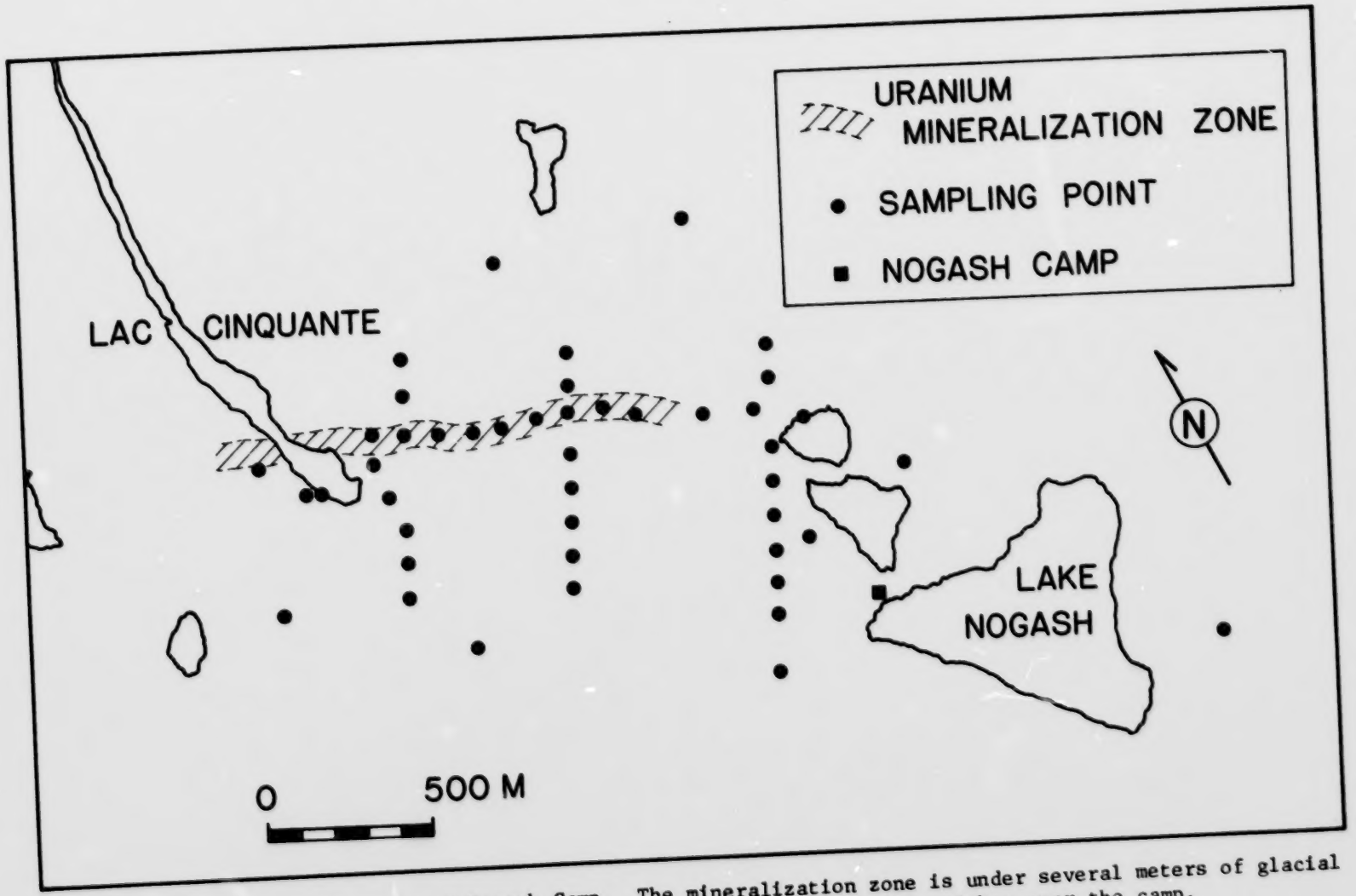

Fig. 2b Detailed sampling map of Nogash Camp. The mineralization zone is under several meters of glacial overburden. Drainage follows an ESE direction towards the three lakes near the camp.

Extensive Study Sites. At "showing" sites, the portable scintillometer was used to identify the region of highest gamma ray flux. This was the first sampling point (usually a dry habitat). Downslope (100-200 m apart), two additional points of mesic and wet habitats were investigated and sampled.

Arbitrary Sites, with no known uranium mineralization, were chosen a priori on the map of Central Keewatin in order to establish the "background" radionuclide levels. The sampling procedure was similar to that employed at the showing sites where a dry site was first chosen by visual inspection of the area. Data were gathered at 19 Extensive sites, from a total of 54 sampling points.

Sampling Procedure. Upon reaching a sampling point, a standard procedure was followed: 1. general information on the environmental characteristics was recorded. These included the topographic location (slope and aspect); the surface conditions (rock outcrops, boulder fields, frost boils, etc.); the moisture condition (drainage and the soil moisture regime classified as dry, mesic or wet); and the plant community type (heath-lichen, sedge meadow, etc.). 2. An area of representative vegetation type was chosen upon which a 50 x 50 cm quadrat with a 5 x 5 cm grid was placed. (This procedure was adopted to optimize data gathering with a minimum number of samples due to logistic constraints in the field.) 3. The gross gamma radiation level was measured at ground level using a portable NaI(Tl) scintillation counter, (Nuclear Enterprise Transcint Model 1001B) in a 3 m radius around the sampled quadrat. 4. The plant diversity and cover within the quadrat were then determined, its vegetation removed and stored for subsequent laboratory analysis. (At all showing sites, individual plant species found growing on the uranium anomaly were collected separately.) 5. Following the removal of the plant cover the depth of permafrost table and characteristics of peat and mineral layers were recorded. A vertical slice (ca. 800 ml) of each substrate layer was collected to a maximum depth of about 60 cm. No samples were collected from below the permafrost table.

Laboratory Methods.

The plant and substrate samples were prepared and analysed at Erindale College, University of Toronto during 1981-1983. A subsample (about 1 L) of the composite vegetation was washed and then dried at 60°C to constant weight. Substrate samples were only dried. A portion of each sample was packed in a Marinelli beaker (500 ml) and analysed using gamma-ray spectrometry. The dry weight of the sample in the beaker ranged between 20 g (plants) and 600 g (mineral substrate). Composite vegetation samples were subsequently manually sorted into their components of lichen, moss, individual vascular plant species and litter, and the dry weight for each component was established. Selected plant species from the sorted composite vegetation were analysed separately for ^{238}U, ^{226}Ra and ^{137}Cs to assess their relative ability to concentrate radionuclides.

A conversion curve was determined for the portable scintillometer in order to convert counting rates to dose rates in milliroentgen per hour (mR/hr) (cf. Lei 1984).

Gamma-Ray Spectrometry. The activities of ^{226}Ra, ^{214}Bi and ^{137}Cs in the samples were determined using gamma-ray spectrometry. The counting system consisted of a Ge(Li) detector (Nuclear Design, ca. 3% efficiency; Counter No. 2), a high voltage power source (Fluke Model 412B), operating voltage: -1200 V, a linear amplifier (Ortec Model 451) and a 4096-channel pulse height analyser (Davidson Model 4106A). A second Ge(Li) detector (Aptec/Nrd, ca. 10% efficiency; Counter No. 1) was later acquired. It was connected to a Power Design (Model AEC-5000) high voltage power source, operating voltage: +1500 V and an Ortec (Model 451) linear amplifier. Due to the difference in the detector efficiencies, the activities measured with Counter No. 1 were normalized to that of Counter No. 2. The output of the spectrometer takes the form of a gamma-ray spectrum in which three gamma ray lines are selected for an intensity determination; their energies are 186 keV (^{226}Ra), 609 keV (^{214}Bi) and 662 keV (^{137}Cs) (Fig. 3a). The activity of a given radionuclide is proportional to the area under the Gaussian peak which is composed of the accumulated counts in an interval of memory channels. To obtain the sample activity, the counts under the peak were integrated and the continuum under the peak was subtracted. The background activity was then also subtracted. This end result is an activity value expressed in counts per 1000 min per g dry wt. The gamma-ray spectra of all samples were recorded on cassettes and a numerical print-out of each spectrum was produced also.

Note: Among the uranium family radionuclides, ^{214}Bi is the most prolific gamma-ray emitter. The 609-keV line is readily identifiable and has the best resolution. However, being a daughter product of the gas, ^{222}Rn, the ^{214}Bi activity is determined by the ability of environment to contain its parent nuclide. In a counting experiment using a Betula glandulosa sample, it was found that drying the plant material drives some of the ^{222}Rn gas out of the sample, resulting in the loss of ^{214}Bi activity. Washing and crushing, however, did not contribute further to the loss. The sample was then allowed to re-establish secular equilibrium (Lapp and Andrews 1972) in a sealed Marinelli beaker. After 4 half-lives ($T_{1/2}$=3.8 days for ^{222}Rn), the daughter product reaches 94% of its equilibrium value (Levinson and Coetzee 1978). It is apparent that ^{214}Bi activities can be below the secular equilibrium value in unprocessed plant samples. This has prompted the use of the 186 keV gamma ray of ^{226}Ra in the data analysis throughout the present study.

The reproducibility of data obtained through gamma-ray spectrometry was also evaluated. Composite vegetation and substrate samples along a transect were analysed on two occasions 16 months apart (Fig. 3b). The aim was to detect possible changes in radionuclide activities after a period of time in storage. No significant differences were found between the two trials using the ^{226}Ra of the substrate. The greatest deviation between the trials of the ^{226}Ra content was observed in composite vegetation samples with < 5 counts/1000 min/g dry wt, where variations greater than 100% can be expected and the detection limit is approximately 1 count/1000 min/g dry wt (or 1 pCi/g) for a 24-hr counting period with the 3%-efficiency counter.

^{226}Ra and ^{137}Cs activities in plant and substrate samples were initially determined as counts/1000 min/g dry wt. For comparative purposes, these values were converted to pCi/g or becquerels per kg (cf. Lei 1984).

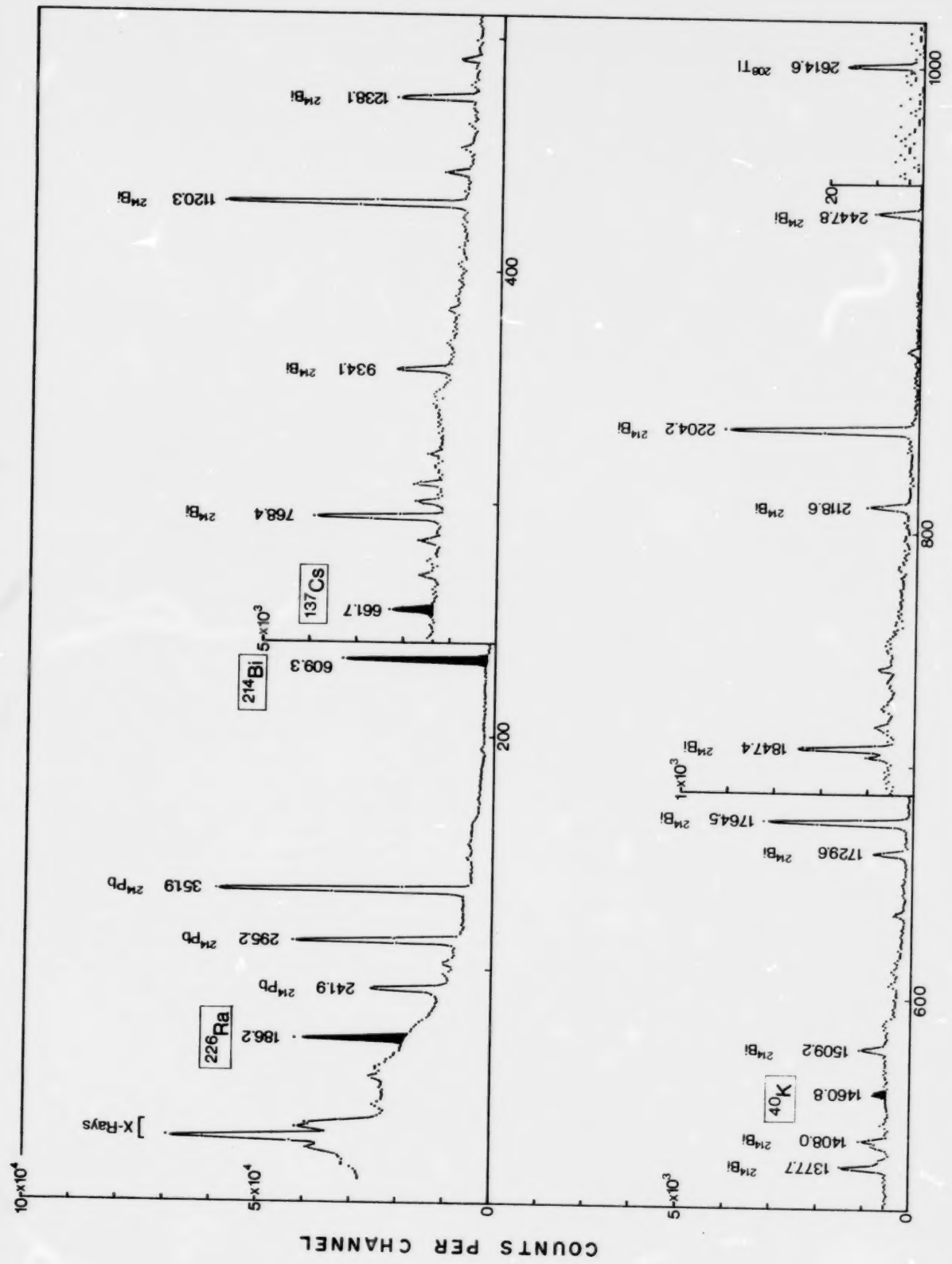

Fig. 3a Typical gamma ray spectrum of an uranium-bearing rock sample from the Lone Gull main showing. The darkened peaks are those used for the analyses of sample.

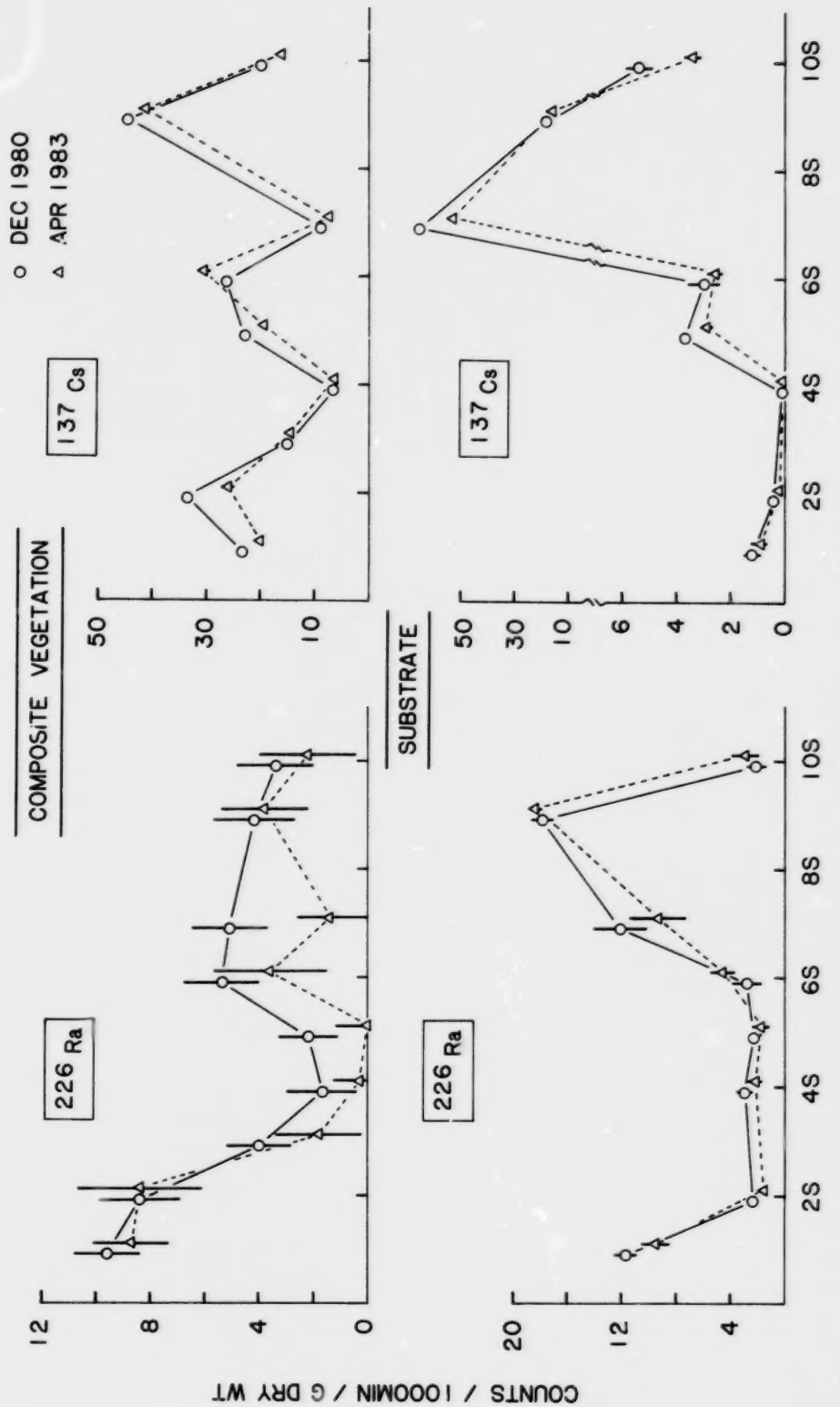

Fig. 3b Reproducibility of observations of the activities of plant and substrate samples taken 16 months apart. The samples were taken from the Lone Gull site.

Delayed Neutron Activiation Analysis. Selected plants and substrate samples were washed, dried and pulverized; substrate samples were dried and passed through 2 mm sieve. Prepared samples weighing 0.6-10 g were put in standard plastic counting vials and analysed for their ^{238}U content at Nuclear Activation Services Ltd. in Hamilton, Ontario.

RESULTS

Radionuclide Survey of Intensive and Extensive Study Sites

Lone Gull Intensive Study Site At Lone Gull, the habitat conditions of the main transects in the four compass directions were as follows:

North: The first 60 m graded downward into the E-trenching valley with considerable terrain disturbances from track vehicles. From 90 m N, the terrain rose (15°) steadily until 270 m N where it levelled off and low hummocks began to appear as the habitat became slightly wetter. The vegetation along this transect was dominated by heath species: Ledum decumbens and Vaccinium vitis-idaea, sedges (Carex aquatilis ssp. stans)and dwarfed willows and birch. Mosses (Dicranum elongatum and Alectoria ochreleuca) represented 20-40% of the cover.

East: The terrain in the valley was disturbed between 30 and 120 m. Further E it became more rugged with frost-heaved bedrock fragments. A beach ridge near 700 m E indicated the inundation of the region (including the Main Showing) by a former proglacial lake. The habitat was mesic between 150 m and 600 m, and consisted mainly of low shrub and heath with a minor component of lichens and mosses. Beyond 750 m, the terrain was relatively flat with frequent hummocks.

South: This transect cut through the catch basin draining the runoff from the Main Showing. The first 120 m was still part of the granitic outcrop with areas of scree and patch vegetation dominated by heaths and lichens. From 150 m onward, the terrain dipped gently (5°) into an expansive sedge meadow. On the hummocks, birch and heath species were dominant with a mossy ground cover.

West: The terrain rose to 200 m from the Main Showing, then descended to the 500 m mark and leveled off to a pond at 920 m. The habitat of the first 300 m was dry-mesic with frequent mudboils (heath-moss). From 400 m to 700 m the surface was dotted with hummocks and frost-heaved bedrock. Low shrub and heaths were common with a minor component of mosses and lichens. Beyond 700 m, the frequency of mossy hummocks increased amidst a sedge meadow.

Substrate: The average thickness of the peat layer was 8 cm and contained 70% OM (organic matter). Peat increased in both thickness and OM in the wetter habitat. The average substrate pH = 5, but dropped to 3.9 where OM was high. The underlying glacial drift was mostly bouldery, embedded in silt and clay. A reducing environment was prevalent in the substrates of the sedge meadows (Gleying) (Figure 4).

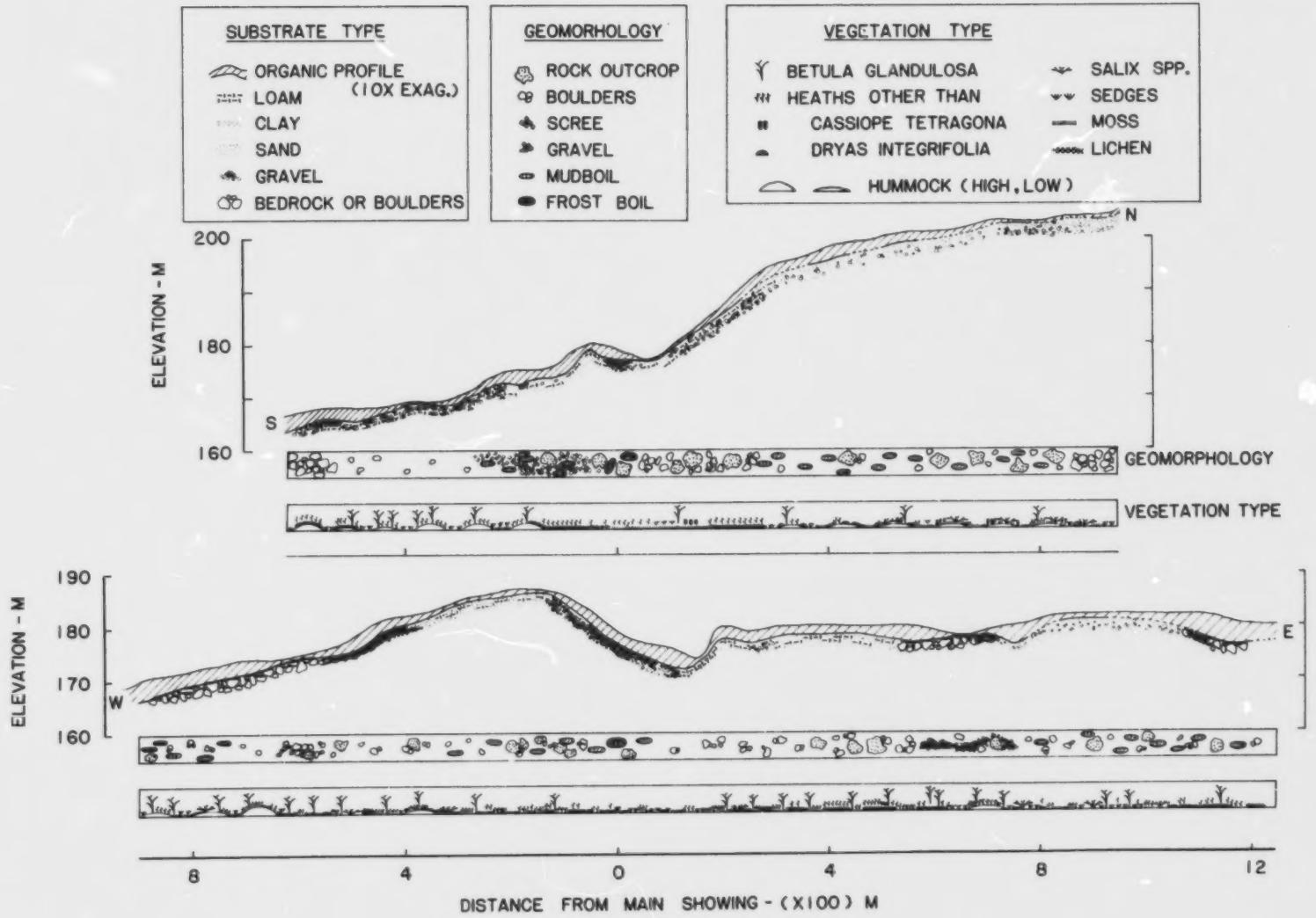

Fig. 4 The surficial environmental profiles of the two transects of Lone Gull Camp. Thickness of substrate underlying the organic layer is not indicated.

The vegetation and substrate samples collected along the N-S and E-W transects revealed distinct anomalies of the natural radionuclides at the Main Showing (Om) and Central Zone (750 m E) (Figs. 5 and 6 respectively). ^{238}U, ^{226}Ra and ^{214}Bi activities were 3-4 orders of magnitude greater at the Main Showing compared to the transect average. In the Central Zone (750 m E) which was lightly buried under glacial drift the activities were about 100 times that of the average. However, the activities fell to very low levels ca. 200 m from the Main Showing.

The average depths of the peat layer analysed along the two transects were comparable.

Substrate ^{226}Ra was lowest in the northern transect and highest in the south, an indication that a southerly migration of ^{226}Ra had occurred following the local topographic gradient. The higher ^{226}Ra activity in the peat layer of the southern transect suggests that this radionuclide was transported downslope, probably by spring runoff. At both the Main Showing and the Central Zone, ^{226}Ra activities were higher in the peat than in the mineral substrate. ^{238}U does not appear to follow this pattern.

The good correlation between ^{238}U and ^{226}Ra activities is of particular significance since these two radionuclides were measured by different techniques.

The ^{214}Bi activity was generally lower than the corresponding ^{226}Ra activity, particularly in the composite vegetation. This is a consequence of the radium-radon disequilibrium during sample preparation as described in Laboratory Methods. Therefore, ^{214}Bi activities will not be discussed from this point on.

The levels of activity were higher in the southern portion of the N-S transect (Figs. 5). This is related to the downslope location from the Main Showing with the drainage directed towards the wet, hummocky terrain (Fig. 4).

Patterns of activity of ^{137}Cs, the fallout product, bear no resemblance to the uranium radionuclides pattern and showed considerable fluctuation (Fig. 5). By contrast, the E-W transect (Fig. 6) showed a fairly consistent level of ^{137}Cs.

^{137}Cs activity was more variable in the substrates than in the composite vegetation. Obviously the topographic and substrate heterogeneity were factors contributing to this element re-distribution. There was a distinct ^{137}Cs high in the peat and mineral substrate of the Main Showing most likely related to the disturbed surface condition of that area. A second prominent ^{137}Cs maximum was evident at a point 270 m S of the Main Showing (Figs. 5) in the area of wet depressions between hummocks. There was a concurrent ^{226}Ra high at this sampling point, which suggests these two radionuclides, although having different points of origin, may be concentrated by the same environmental mechanisms, most probably by spring run off.

The highest ^{137}Cs value was found in the peat of 270 m S (34 pCi/g).

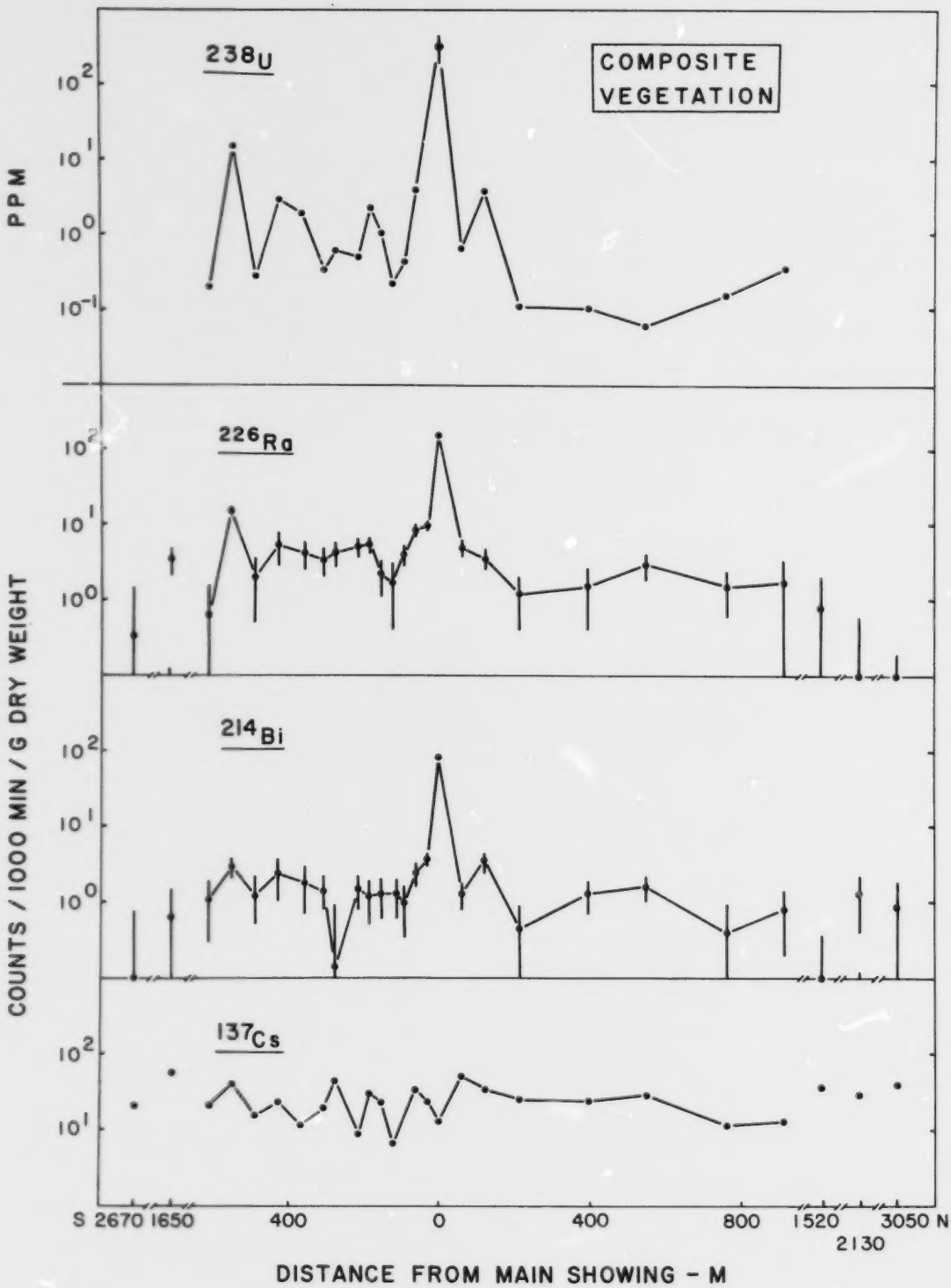

Fig. 5a The radionuclide activity profiles of the composite vegetation along the N-S transect of the Lone Gull site.

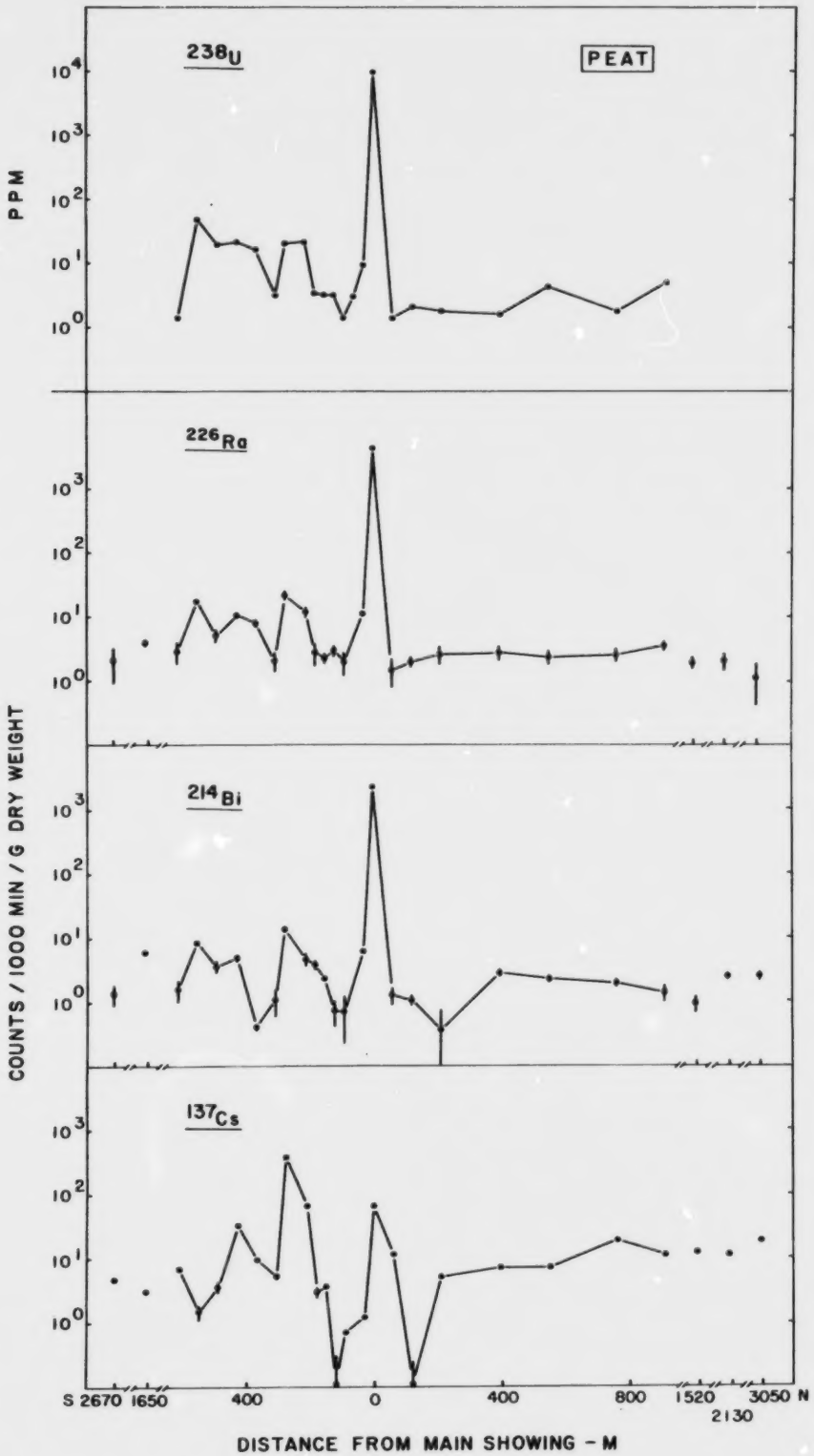

Fig. 5b The radionuclide activity profiles of the peat along the N-S transect of the Lone Gull site.

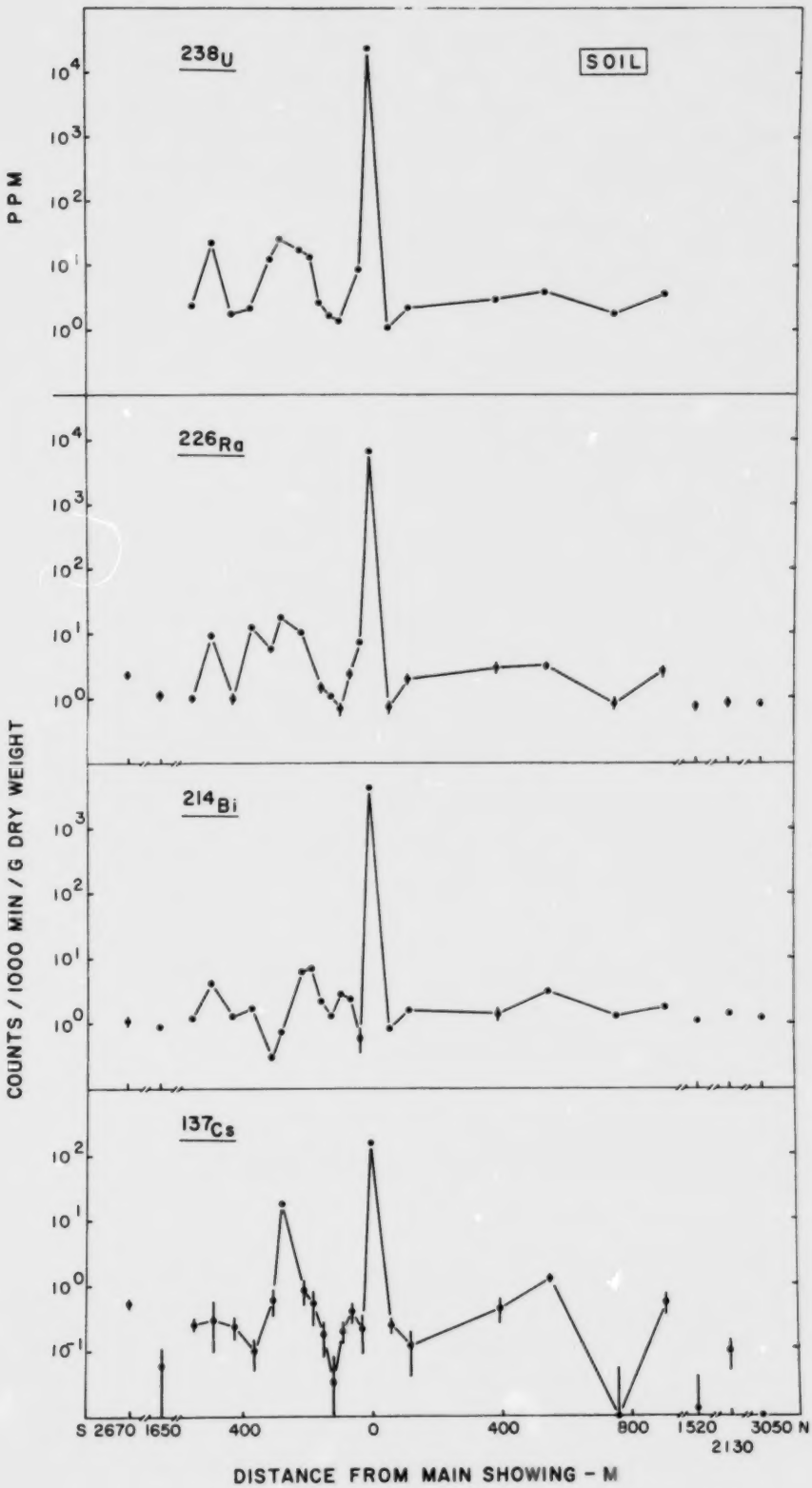

Fig. 5c The radionuclide activity profiles of the soil along the N-S transect of the Lone Gull site.

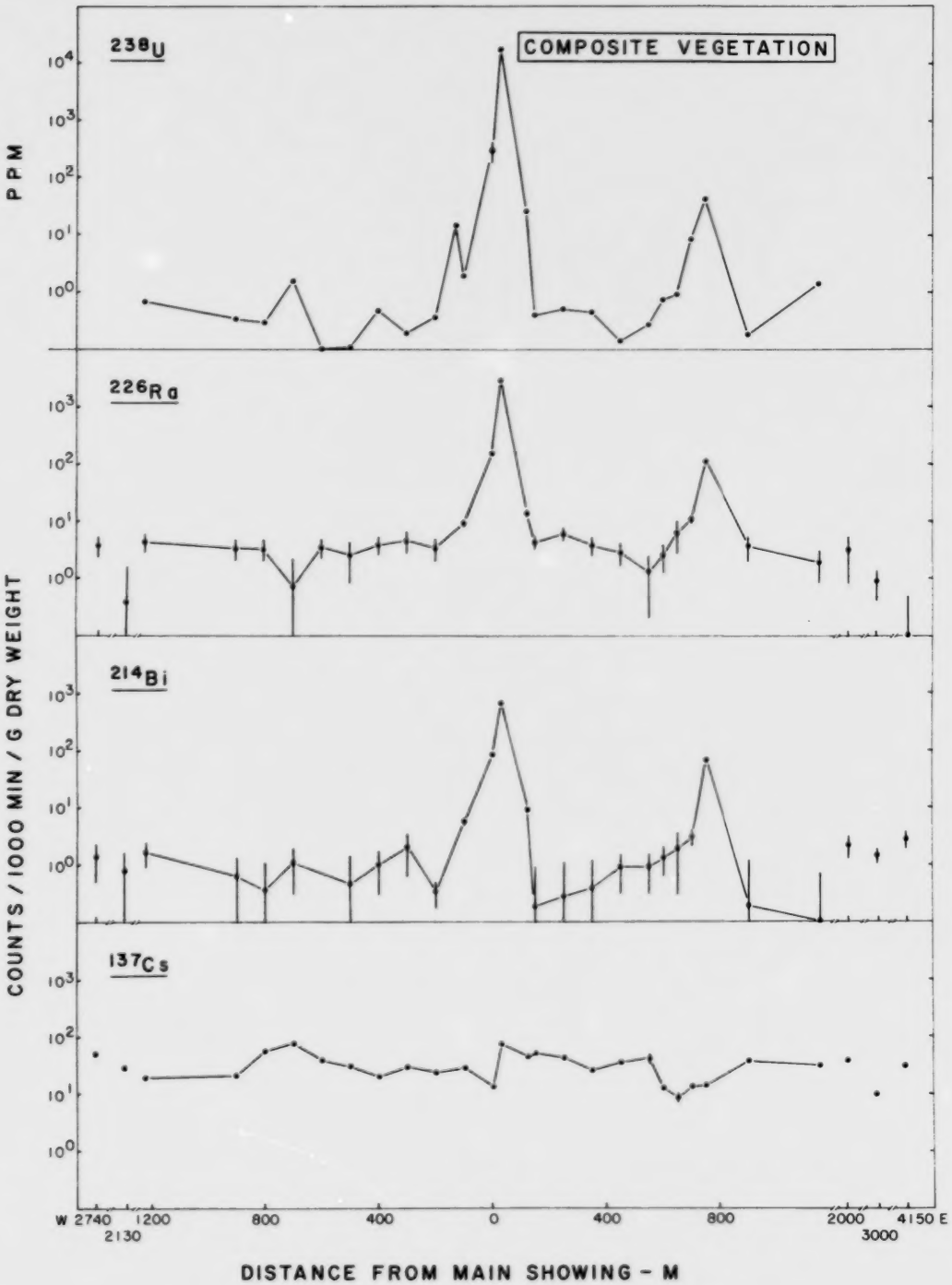

Fig. 6a The radionuclide activity profiles of the composite vegetation along the E-W transect of the Lone Gull site.

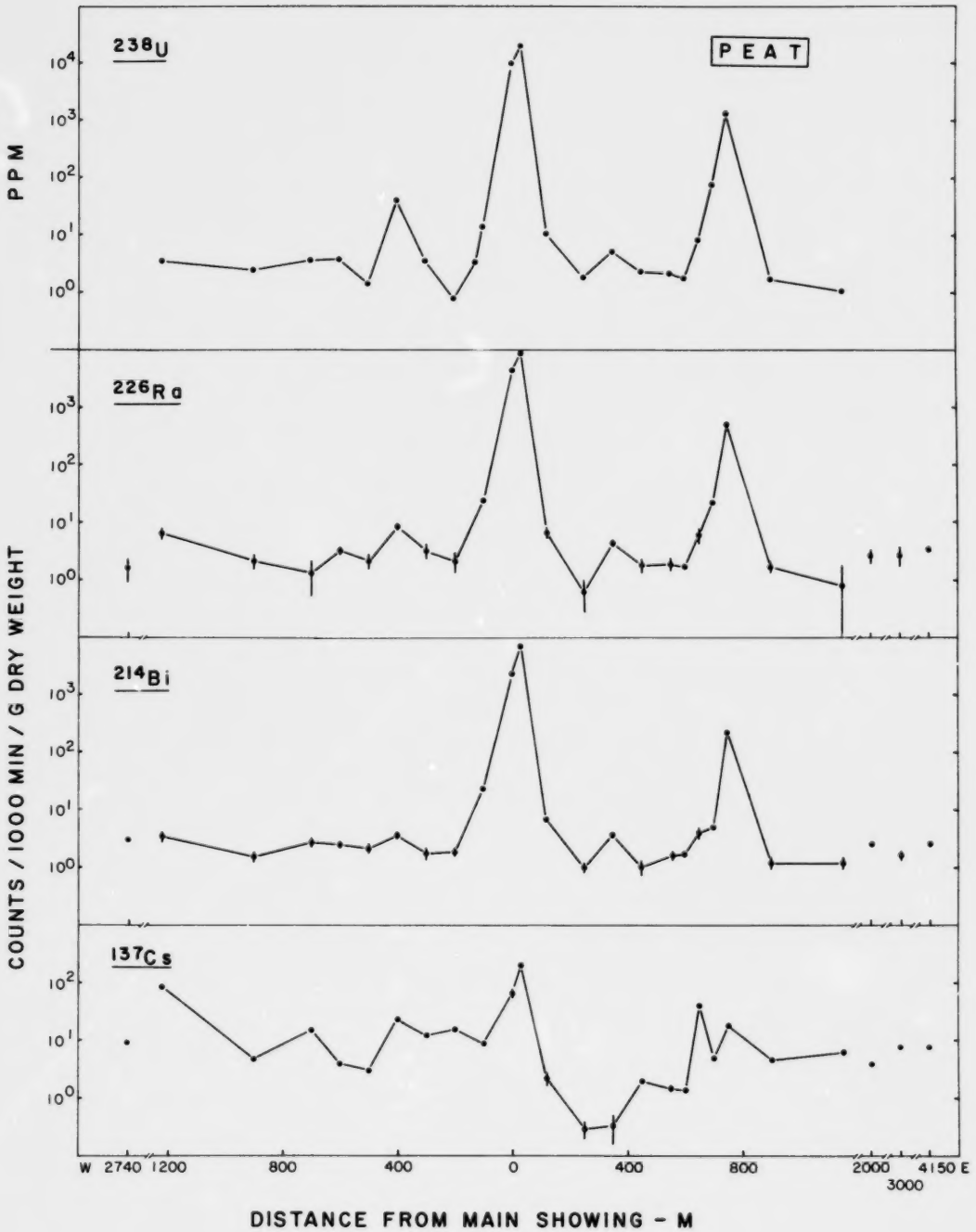

Fig. 6b The radionuclide activity profiles of peat along the E-W transect of the Lone Gull site.

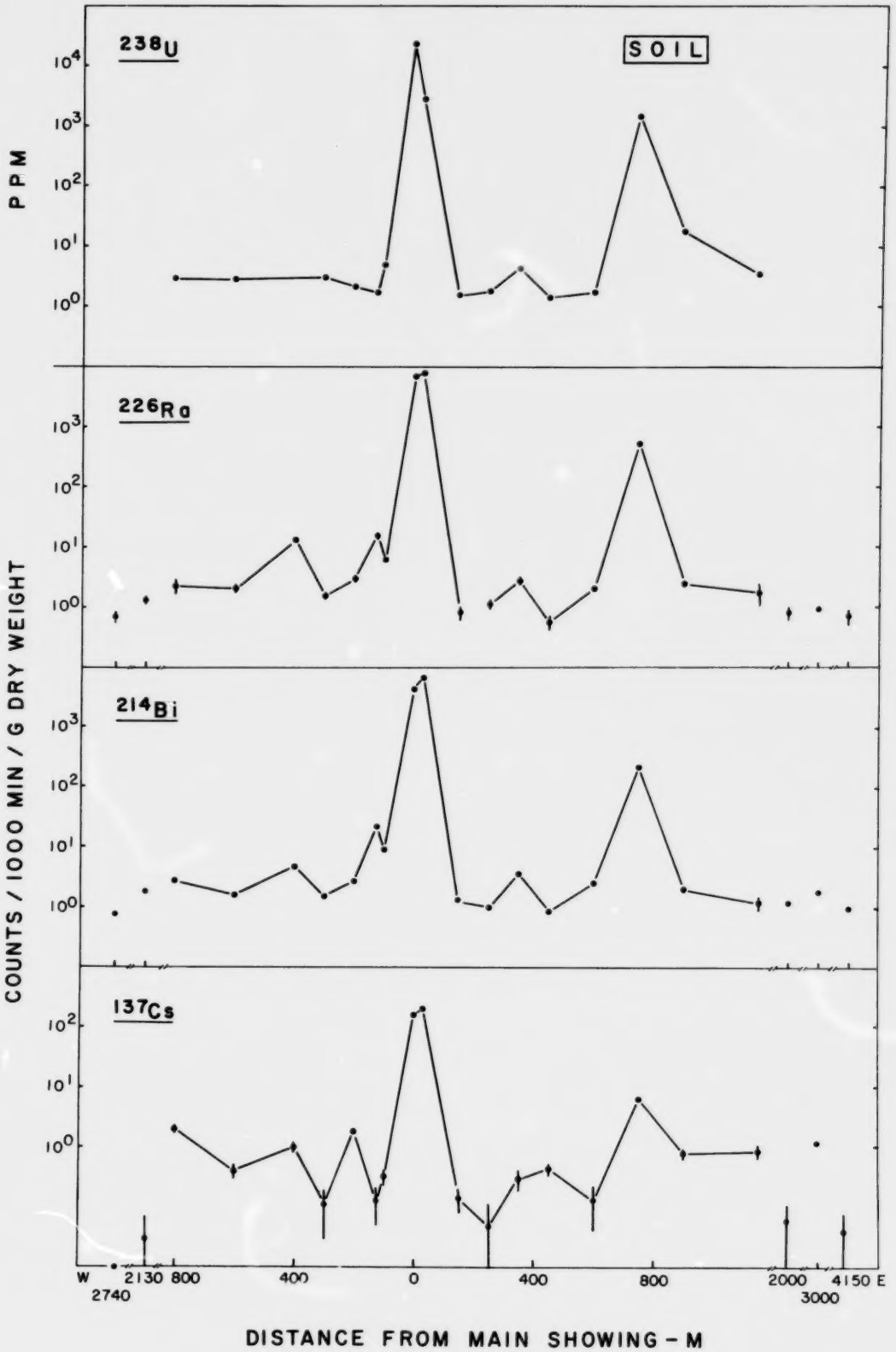

Fig. 6c The radionuclide activity profiles of the soil along the E-W transect of the Lone Gull site.

The portable NaI(Tl) scintillometer detected a pattern of radiometric anomalies similar to those revealed by the later Ge(Li) spectrometric analysis conducted later in the laboratory.

In 1982, extensive drilling was undertaken at Lone Gull, by Urangesellschaft Canada Ltd. Fresh "mud" extruded from six recently drilled holes (between 700 m and 950 m E of the Main Showing) were sampled. Five of the "drill mud" samples contained moderately high levels of ^{226}Ra (23.3-150 [ave. 88.8] counts/1000 min/g; one (at 900 m E) was very high with 2200 counts/1000 min/g (or 2.3 n Ci/g)).

Nogash Intensive Study Site. The area around Nogash Camp was intensively prospected by Pan Ocean Oil Ltd. of Calgary in 1981. Considerable amount of drilling took place that summer and terrain disturbance (vehicle tracks and drilling discharge) was widespread.

The uranium mineralization at Nogash is associated with hematite-alteration veins or "gash veins" which occur within basaltic outcrops. The gross gamma-ray intensity reached 400,000+ cpm over the pitchblende visible in the "gash veins". The area had an abundance of erratics, some of which were radioactive.

The main mineralization zone lies under >20 m of glacial overburden and stretches about 1.5 km in a SE direction from Lac Cinquante. It forms a drainage basin with a thick layer of water-saturated peat and coarse glacial drift underlying the peat. This basin receives about 10% of the drainage from the local watershed which drained into small lakes north of the camp.

Nogash Camp area was characterized by scattered stands of white spruce (Picea glauca). Willows (1.5 m) formed dense thickets.

The western end (east of Lac Cinquante) of the main transect was wet-mesic with a hummocky sedge meadow prevailing. The dominant species were Carex aquatilis ssp. stans and C. rariflora with extensive areas of thick moss (Sphagnum spp. and Hylocomium splendens). Vaccinium uliginosum and Ledum decumbens and Rhododendron lapponicum occurred on the hummocks. Drier sites supported a Birch-Heath community.

The three perpendicular transects intercepted the mineralization zone as well as the two drainage basins. Most of the points were in mesic to dry-mesic habitat with a Low Shrub-Heath-Moss community.

Substrate: The wet areas had a highly organic surface layer (10-15 cm). The mineral layer had less than 5% OM. The proportions of sand, silt and clay were similar to Lone Gull at an average of 60:20:20.

The analyses of plant material could not lead to identification of this uranium mineralization site (Fig. 7a). At Lone Gull (the Main Showing values excluded) ^{226}Ra levels in composite vegetation showed a higher average activity than were the means at Nogash. This suggests the presence of a geochemical halo (an area of anomaly surrounding the mineralized source) at Lone Gull but not at Nogash.

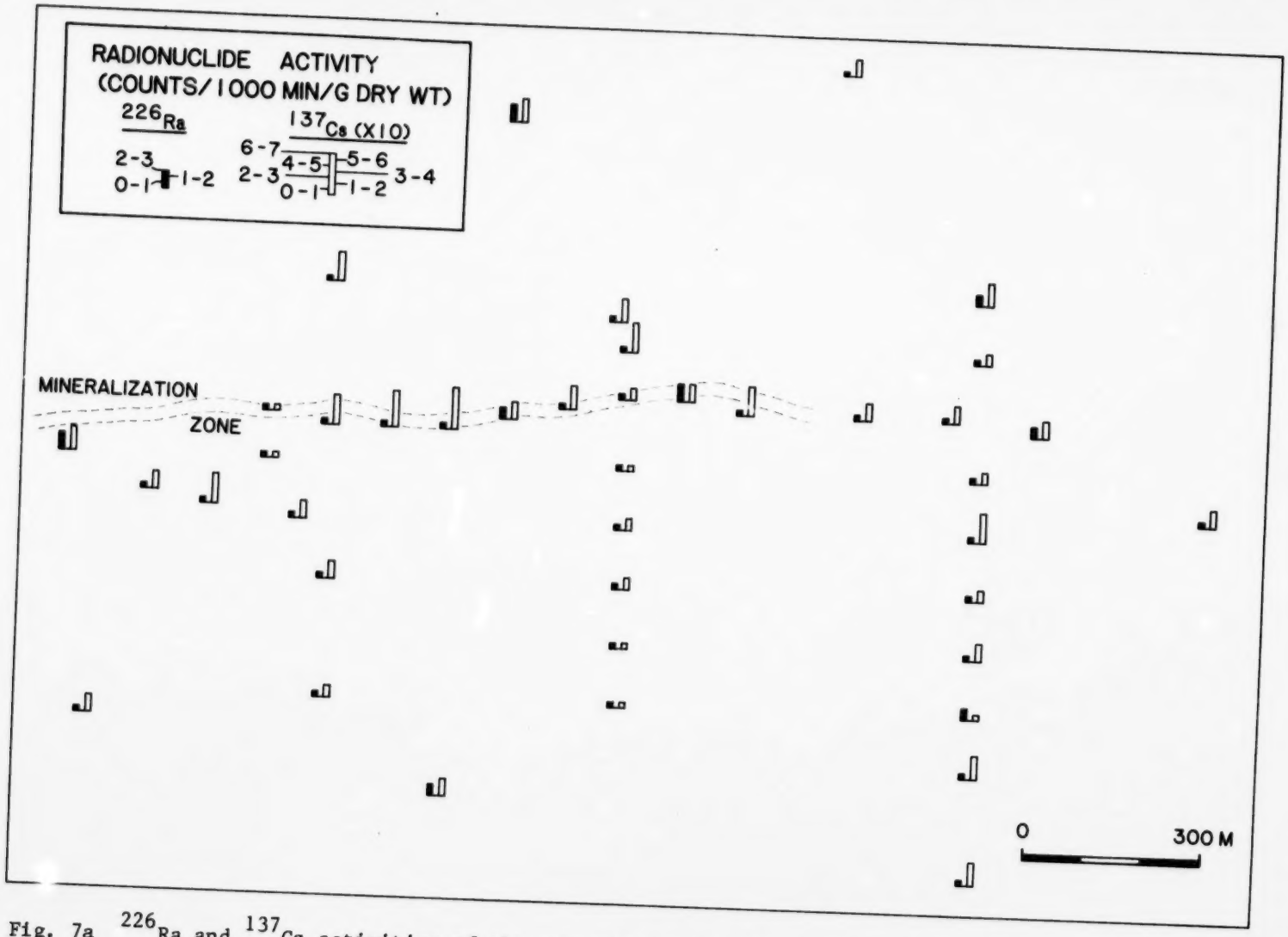

Fig. 7a ^{226}Ra and ^{137}Cs activities of the composite vegetation samples taken at the Nogash site.

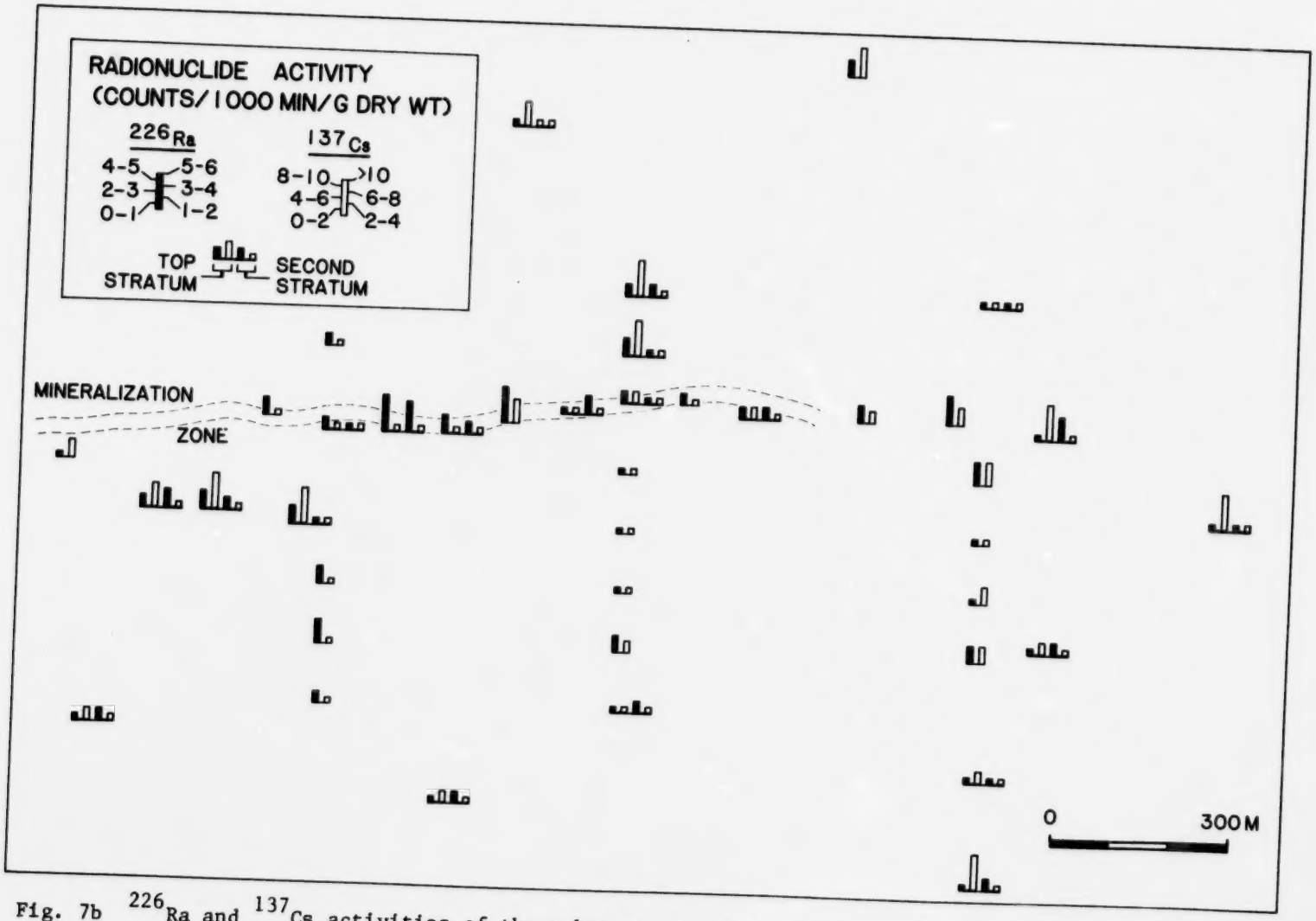

Fig. 7b ^{226}Ra and ^{137}Cs activities of the substrate samples taken at the Nogash site.

The activities encountered along the mineralization zone were not very different from those of other sampling points. In the substrate, ^{226}Ra activities were slightly higher and showed signs of association with the mineralization zone (Fig. 7b).

The ^{137}Cs levels in composite vegetation were not significantly different at both localities but the substrate levels were higher at Lone Gull. In the substrate ^{137}Cs showed a correlation with the local drainage pattern with higher activities measured in the wetter areas.

Extensive Sampling Sites: In Central Keewatin the dry habitats are rich in lichens with Cetraria and Alectoria species being most common. The vascular plants are Vaccinium Vitis-idaea, Empetrum nigrum and Arctostaphylos alpina. Hierochloe alpina is often present on ridges and eskers.

Greater species diversity was observed in the mesic habitats. Heath species Cassiope and Empetrum occurred in dense patches. Lichens maintained their abundance with local occurrences of Stereocaulon albicans, Thamnolia vermicularis and Dactylina arctica. Mosses Dicranum elongatum, Polytrichum spp. and Racomitrium lanuginosum dominated the mesic sites. Other common species were Betula glandulosa, Epilobium latifolium, and legumes Astragalus alpinus, Hedysarum alpinum and Oxytropis maydelliana. Dryas integrifolia was abundant on mesic slopes.

The wet habitat was represented by extensive sedge meadows. Eriophorum angustifolium, Carex spp. and Scirpus caespitosus dominated the landscape, and Sphagnum spp., Hylocomium splendens and Drepanocladus revolvens were the dominant ground cover species. Willows and birch occurred on the drier hummocks with Andromeda polifolia and Rubus chamaemorus.

^{226}Ra and ^{137}Cs activities (pCi/g) in the composite vegetation and the substrates in geographical groupings of the northwestern, central and southern Keewatin sites are presented in Figures 8a-d. The surface substrate layer is designated as S1, the second layer is S2 and so on.

Extensive Sites (Fig. 8b)

Sand Lake (SND) was situated on an esker. Detectable amounts of ^{226}Ra were present in the S2 of mesic habitat and in the composite vegetation and S1 of the wet habitat. ^{137}Cs activity was between 7.3 and 11.8 pCi/g in the composite vegetation and in traces in the top substrate layer.

Dragon Point (DP) was on a weathered esker and the organic layer was better developed here. No ^{226}Ra was detected in composite vegetation and low amounts (0.7-2.1 pCi/g) were present in the substrate of all three sites. In the dry and mesic habitats ^{137}Cs decreased down the profile but in the wet habitat, ^{137}Cs was found higher in the substrate than in the plants above.

Whalebone Hill (WBH) was a plateau of barren rocks and dry-mesic pockets of vegetation. This site is within an area containing localized concentration of uranium within veins (Miller 1982, per. comm). However,

only background levels of radioactivity were detected at a dry site. The plant and substrate averaged 0.9 pCi/g of ^{226}Ra in the S1 and S2 with no activity in the composite vegetation. ^{137}Cs was similar to Dragon Point dry habitat.

Whalebone East (WBE) was located on another plateau 6 km ENE from Whalebone Hill. Our scintillometer search failed to locate assumed uranium veins, but there were detectable amounts of ^{226}Ra in the composite vegetation on the dry plateau. The mesic habitat had elevated levels of ^{226}Ra in composite vegetation and S2 (1.9 pCi/g). S1 (25 cm thick) was the highest with 20 pCi/g. The ^{137}Cs in the vegetation and substrates was negligible.

Grant Lake (GL) was flanked on its eastern shore by an esker. The scintillometer readings at the ridge-top and at the mesic E-facing slope were elevated at 5220 and 5570 cpm respectively. There was a trend towards higher substrate ^{226}Ra from the dry to the wet habitat. ^{137}Cs activity in the substrate of the dry habitat increased from S1 to S2, just the opposite to the trend observed in other sites.

Tundra Rose (TR) in the Marjorie Hills has areas of uranium-phosphate-cemented sandstone (Miller per. comm.). However a very low amount of ^{226}Ra was present. ^{137}Cs in the top substrate layer was 18% higher than the average of all the Extensive Sites.

Baker Lake North (BLN) was a locality about 10 km NW of the hamlet of Baker Lake. Natural radionuclides were similar to Tundra Rose; the ^{137}Cs activity was higher however.

Central Sites (Fig. 8c)

Forde Lake (FRD) site was 25 km NW of the western shore of Forde Lake. A discrete uranium rock outcrop with > 400,000 cpm scintillometer readings was located. In fact, the entire area had anomalous radioactivity of 10,400 and 6,820 cpm in the mesic and wet habitats. Similarly, anomalous levels of ^{226}Ra were detected in all samples. In dry habitat vegetation ^{226}Ra was 30 times the activity found in the mesic habitat. ^{137}Cs in the mesic substrate samples was similar to that of Grant Lake dry habitat.

Kazan River I (KR1) was located in an area of uranium mineralization that has been prospected. The site sampled was, however, not mineralized. All samples contained less than 2.5 pCi/g of ^{226}Ra. ^{137}Cs in the composite vegetation of the three habitats was fairly consistent (7.4-10.3 pCi/g).

Kazan River II (KR2) was 3 km S of Kazan River I with similar ecological characteristics. The scintillometer reading at the uranium showing was 380,000 cpm, diminishing to ca. 5000 cpm in the adjacent areas. Elevated levels of ^{226}Ra were detected in the composite vegetation and S1 of the mesic "showing" habitat. Small amounts of ^{226}Ra were present in the dry habitat samples and in composite vegetation of the wet habitat. ^{226}Ra content in the substrate of the wet habitat was not different from non-mineralized wet sites. The pattern of distribution for ^{137}Cs was quite similar to that observed at Kazan River I.

Kazan Falls South (KFS) contained a high-grade uranium mineralization; the showing was disturbed. To avoid contamination, a mesic sampling point was chosen 5 m from the excavated pit. Scintillometer readings indicated 23,700 cpm in the mesic and 27,900 cpm in the wet habitat. Anomalous ^{226}Ra activities were detected in the mesic and wet habitats while background conditions prevailed at the dry habitat. In S2-wet, the ^{226}Ra activity of 195.7 pCi/g was the highest among all the samples collected from the Extensive Sites. Substrate ^{137}Cs was greater in the wet habitat than in the other two.

Bissett Lake (BST) had a detectable, undisturbed uranium anomaly. With scintillometer readings between 4,500 and 16,000 cpm, due to scattered radioactive rocks. Elevated levels of ^{226}Ra were found in the samples of the dry site. The activity pattern of ^{137}Cs in the samples closely resembled that of Kazan River I.

Christopher Island (CRI) showed a widespread but low geochemical anomaly having "hairline uranium veins" (Miller, 1982 per. comm). However, only composite vegetation of mesic and S2-wet habitats showed elevated levels of ^{226}Ra. ^{137}Cs activities were similar to other sites.

Southern Sites (Fig. 8d).

Nuturawit Lake (NUT) revealed a weak scintillometer anomaly at the mesic habitat. This was not reflected in the ^{226}Ra activity. ^{137}Cs in S2-dry was higher than most other samples at comparable depths.

Kamilukuak South (KL) was the most southwesterly locality within the forest-tundra ecotone heavily overgrown with willows and dwarf birch. This locality exhibited moderate radiometric reading. Elevated ^{226}Ra was detected only in S1-dry. The pattern of ^{137}Cs distribution was similar to other sites.

Banks Lake (BNK) was another esker with no uranium mineralization. However detectable amounts of ^{226}Ra were found in the composite vegetation and substrates of dry and mesic habitats indicating the presence of a uranium-bearing fraction in the esker material. It was unusual to find a small amount of ^{137}Cs in S3-mesic at 20-40 cm.

Nowleye Lake (NOW), NE of Kamilukuak, is still within the ecotone but it exhibits a reduced shrub growth. The minor radiometric anomaly was restricted to an outcrop of about 1 km across. The only anomalous activity of ^{226}Ra was found in S1-dry with 7.5±1.1 pCi/g. ^{137}Cs activity was within the range of other sites.

Kaminuriak Lake (KN) was a non-mineralized site with a background level of radioactivity and low ^{226}Ra except in S2-wet which was slightly above average. ^{137}Cs in the composite vegetation of the dry habitat was higher than the average.

Rankin Inlet (RI) was the most easterly site. Samples were collected about 1.5 km W of the town of Rankin Inlet on the east side of the airstrip. ^{226}Ra was lower than the average for the non-mineralized sites. ^{137}Cs activities were comparable to other sites.

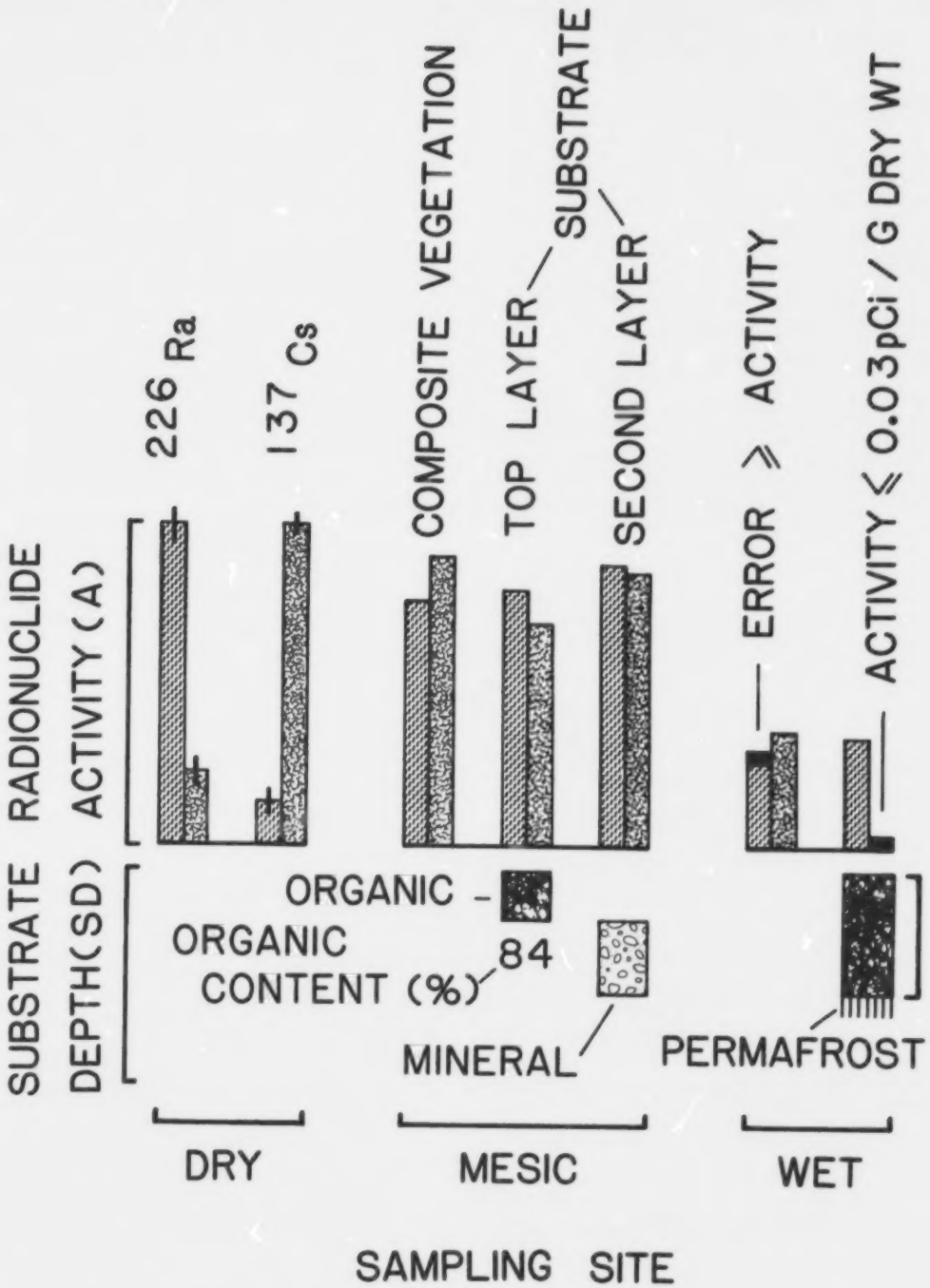

Fig. 8a Legend for figures 8 b, c and d which show the ^{226}Ra and ^{137}Cs activities in composite vegetation and substrate samples taken at the extensive sites.

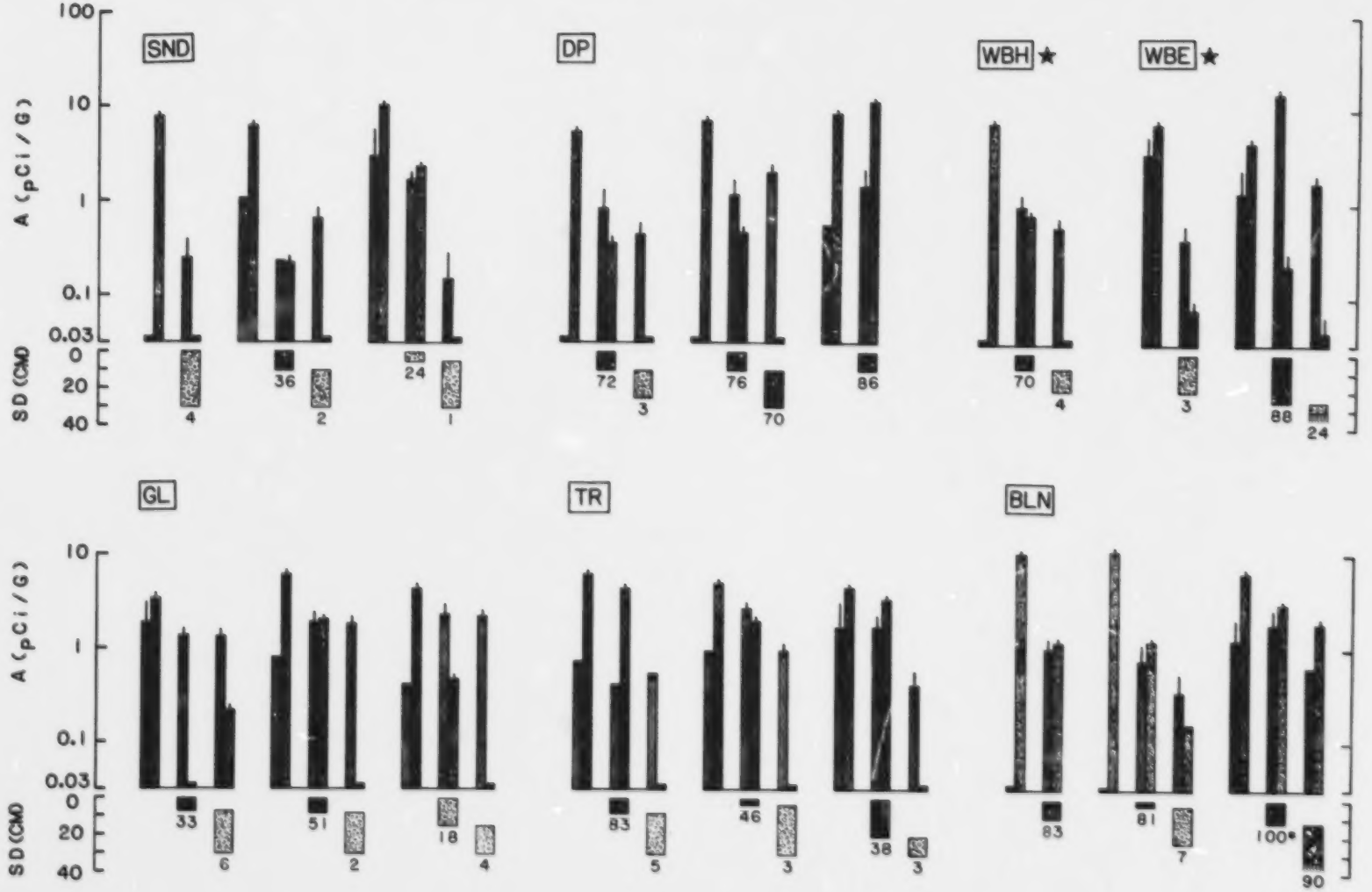

Fig. 8b ^{226}Ra and ^{137}Cs activities over the northern region of the study area.

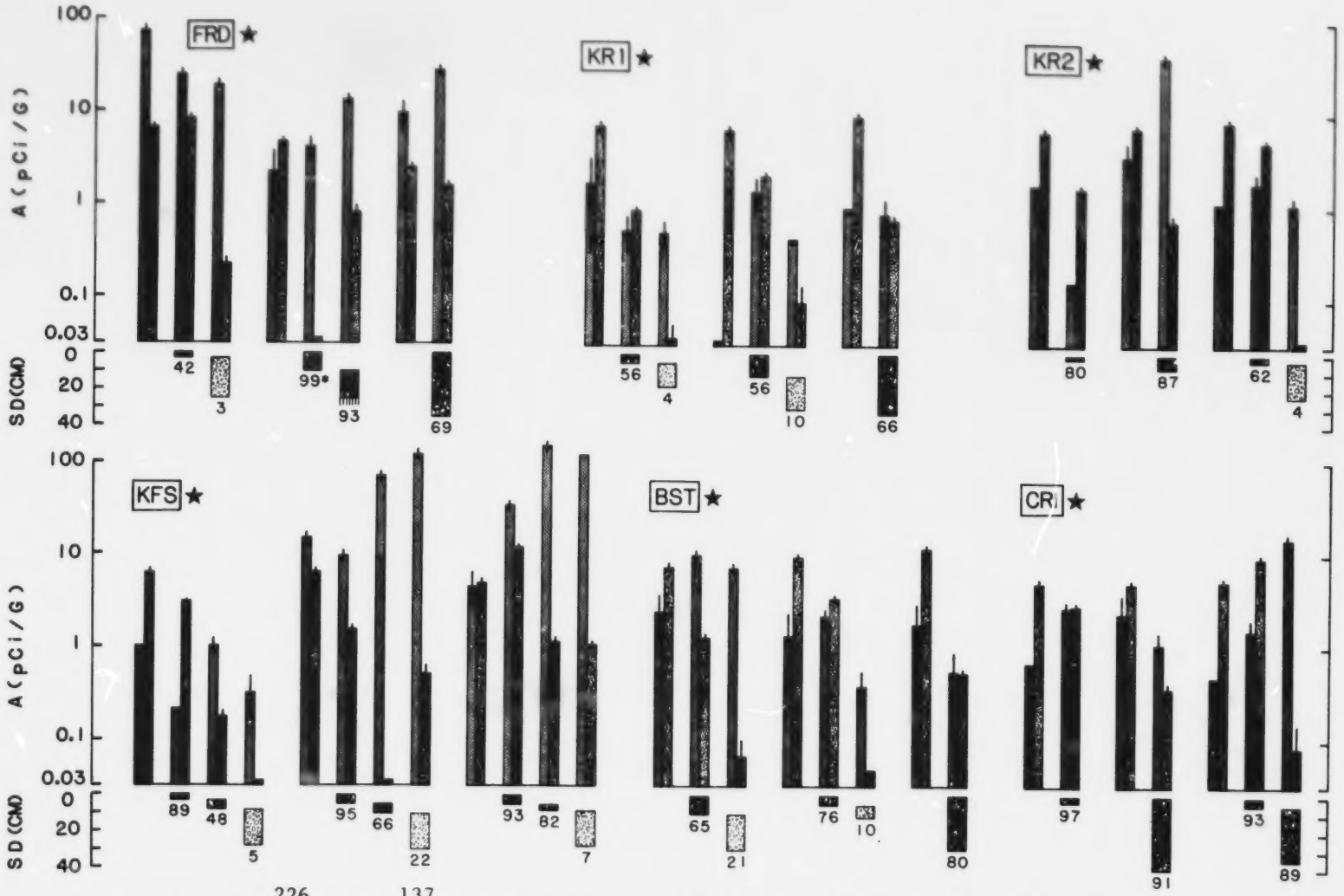

Fig. 8c ^{226}Ra and ^{137}Cs activities over the Central region of the study area.

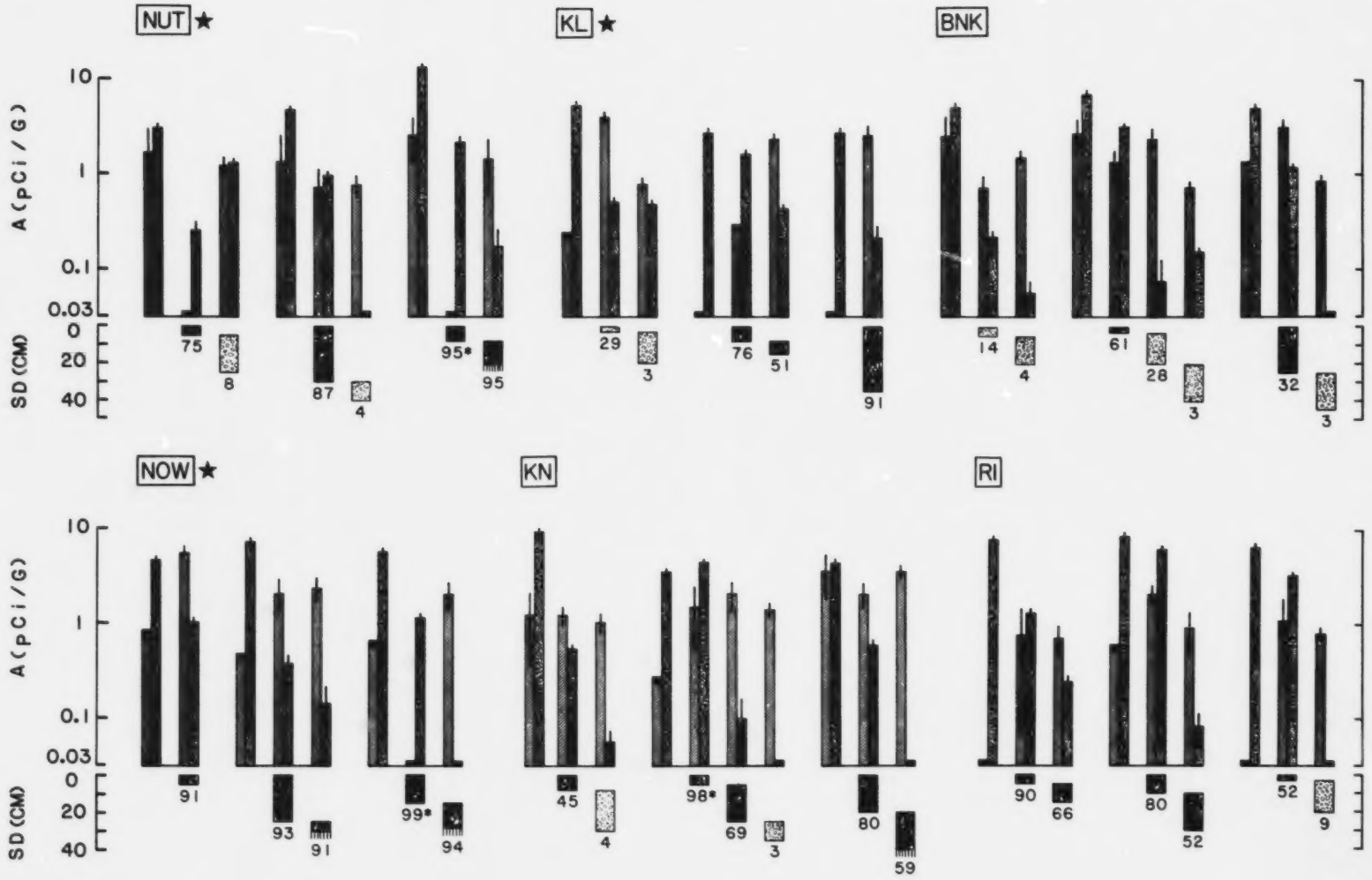

Fig. 8d ^{226}Ra and ^{137}Cs activities over the Southern region of the study area.

Factors Affecting the Distribution of Radionuclides

The relationship between the concentrations of ^{226}Ra in the composite vegetation and the substrate and ^{137}Cs in the composite vegetation and the substrate were examined at Lone Gull, Nogash and Extensive Sites.

At Lone Gull site the correlations were strongly affected by the data from the Main Showing (Table 1). When all the values from Lone Gull were used in the analysis, the correlations for ^{226}Ra acd ^{137}Cs between the composite vegetation and the substrate were highly significant ($r=0.85$ for ^{226}Ra and $r=0.24$ for ^{137}Cs, $p<0.01$ for both). This suggests a direct relationship between the composite vegetation and the substrate. When the values from the four sampling points within 125 m of the Showing were excluded from the calculation, the correlation for ^{226}Ra remained significant ($r=0.81$), but that for ^{137}Cs became non-significant ($r=0.08$). This suggests that, for ^{137}Cs, a relationship between the concentration of this radionuclide in the composite vegetation and that in the substrate does not exist, while it remained strong for ^{226}Ra, quite independently of the data from the Main Showing.

Both ^{226}Ra and ^{137}Cs in the substrate increased with increasing clay content (SRa vs. CLAY and SCs vs. CLAY, Table 1), suggesting that clay has the capacity to adsorb and concentrate both radionuclides. Sand, on the other hand, showed a negative correlation with the radionuclide concentrations. ^{226}Ra in the composite vegetation was also significantly correlated with substrate clay content.

Nogash Site. The significant correlations show that ^{137}Cs in the substrate increased with increasing organic matter content, and it decreased with increasing clay content and substrate depth (Table 2).

In contrast to Lone Gull, however, there was no significant correlation between concentrations of ^{226}Ra in the composite vegetation and that in the substrate, obviously due to the very low levels of ^{226}Ra in the substrate and no detectable amount in the composite vegetation at Nogash, even directly over the zone of uranium mineralization.

Extensive Sites. ^{226}Ra in the composite vegetation was significantly correlated with ^{226}Ra and ^{137}Cs in the substrate, but these two radionuclides were not correlated in the substrate (Table 3). This situation also existed at Lone Gull. This suggests that ^{137}Cs is accumulated at sites of ^{226}Ra anomaly but these two radionuclides do not occur in the same stratum of the substrate profile. ^{226}Ra and ^{137}Cs tended to concentrate at the opposite ends of the vertical soil profile. The clay content was shown to increase with substrate depth.

Substrate pH appears to have a direct positive influence on ^{137}Cs content (SCs vs. pH). This supports the notion that acidic conditions enhance the removal of ^{137}Cs from the substrate.

Radionuclide Correlations Using Pooled Data. Highly significant correlations of ^{226}Ra concentration between composite vegetation, peat and mineral soil were obtained by pooling ^{226}Ra values from all sampling sites

Table 1. Correlation coefficients of radionuclide activities and substrate parameters for Lone Gull. Sample size > 57.

CVRa - ^{226}Ra in composite vegetation
CVCs - ^{137}Cs in composite vegetation
SRa - ^{226}Ra in substrate
SCs - ^{137}Cs in substrate
Sand, Silt and Clay - soil fractions
OM - organic content
pH - substrate pH
SDEP - substrate depth (mean)
SCINT - field scintillometer reading
MOIREG - substrate moisture regime
DIST - distance from Main Showing

*** - p<0.001
** - p<0.01
* - P<0.05
NS - not significant

CVRa	- CVCs	I§	0.35	**	Sand	- Silt	-0.83 ***
		II	-0.07	NS		- Clay	-0.74 ***
	- SRa	I	0.85	***		- DIST	-0.33 *
		II	0.81	***			
	- Sand		-0.31	*	Silt	- pH	0.49 ***
	- Clay		0.56	***		- MOIREG	-0.34 **
	- SCINT	I	0.71	***		- DIST	0.36 **
		II	0.52	***			
					Clay	- Silt	0.30 *
CVCs	- SRa		0.26	***		- OM	-0.32 *
						- DIST	0.27 *
SRa	- Sand		-0.30	*			
	- Clay		0.56	***	OM	- pH	-0.29 ***
	- SCINT		0.47	***			
					pH	- MOIREG	0.38 ***
SCs	- CVRa		0.55	***		- DIST	0.33 ***
	- CVCs	I	0.24	**			
		II	0.08	NS	SDEP	- Sand	-0.54 ***
	- SRa	I	0.62	***		- Clay	0.32 *
		II	0.04	NS		- OM	-0.57 ***
	- Sand		-0.30	*		- pH	0.63 ***
	- Clay		0.55	***			
	- OM	I	0.19	*	SCINT	- DIST	-0.31 **
		II	0.23	**			

§I - values from three Main Showing points (Main Showing, 30 m E and 125 m W) included in analysis

II - values from these points not included in analysis

Table 2. Correlation coefficients of radionuclide activities and substrate parameters for Nogash. Only significant pairs are shown. ()=sample size. For legend, see Table 1.

CVCs	- pH	0.62	(13)	*
SCs	- Clay	-0.74	(8)	*
	- SDEP	-0.33	(59)	**
Silt	- MOIREG	-0.71	(8)	*
OM	- SCs	0.86	(13)	***
	- SCINT	-0.74	(9)	*
SDEP	- pH	0.62	(13)	*

Table 3. Correlation coefficients of radionuclide activities and substrate parameters for the Extensive Sites. Sample size≥43. Only significant pairs are shown. For legend, see Table 1.

CVRa	- SRa	0.22	*
	- SCs	0.21	*
CVCs	- MOIREG	-0.18	NS
SRa	- Clay	0.45	**
SCs	- OM	0.35	***
	- pH	0.22	*
	- SDEP	-0.45	***
Sand	- Silt	-0.95	***
Silt	- Clay	0.39	**
	- OM	0.32	*
Clay	- Sand	-0.67	***
OM	- SDEP	-0.42	***

(Fig. 9). The lower ^{226}Ra values (solid circles) in these figures are averages from 10 to 70 data points. The higher ^{226}Ra values (open circles) represent single sampling points at known uranium showings. The slopes of the three regression curves dropped from 0.89 to 0.71 to 0.65 which indicates a more intimate mineral association between the two substrate layers than between the substrates and the vegetation. The ^{226}Ra in the composite vegetation, however, remains highly correlated with the substrate ^{226}Ra. This suggests that, despite the varying composition of plant species between sampling points, vegetation has the capacity to reflect the concentration gradient of ^{226}Ra in the substrate.

^{238}U, ^{226}Ra and ^{137}Cs in Plants

Common Vascular Species. The feasibility of plant biogeochemistry related to uranium showing was investigated by analysing plant species collected from various localities.

Sedges were represented mainly by Carex and Eriophorum species. No detectable amounts of ^{226}Ra were present. The average ^{137}Cs activity in sedges was higher than in most species (0.9 pCi/g) associated. However, with the highest standard error (±19%). Salix spp. from the showing sites of Kazan River II and Lone Gull contained detectable amounts of ^{226}Ra (1-14 pCi/g), but the ^{137}Cs content was among the lowest. Betula glandulosa from the Lone Gull and Nogash sites had no detectable ^{226}Ra away from the showings. Highly anomalous values (35-170 pCi/g) of ^{226}Ra were detected at the showing sites of Forde and Kazan Falls South. ^{137}Cs activity was low (0.5-2.8 pCi/g). Dryas showed the second highest mean ^{137}Cs value (3.7 pCi/g). The amount of ^{226}Ra was undetectable.

^{226}Ra concentrations in Empetrum nigrum at the showing sites of Forde and Kazan River II were elevated (2-20 pCi/g) but not at other sites. The mean ^{137}Cs activity was modest at 0.5 pCi/g. Arctostaphylos was the only species collected from the uranium showing at the Christopher Island site which contained a measurable amount of ^{226}Ra (at 1.2 pCi/g). The average activity of ^{137}Cs was 0.5 pCi/g. Ledum decumbens was the only species having a detectable concentration of mean ^{226}Ra (0.26±0.09 pCi/g); however, 6 of the 8 samples had essentially no ^{226}Ra. The average activity of ^{137}Cs was 0.8 pCi/g. Except for V. uliginosum, all species collected from the Forde showing site contain more than 9.5 pCi/g of ^{226}Ra.

Most plants taken from non-mineralized sites showed levels of ^{238}U below 0.5 ppm. Those plants collected from showing sites contained elevated concentrations of ^{238}U, up to 240 ppm (Arctostaphylos alpina from Forde Lake).

Lone Gull Main Showing Site. Plants growing in the vicinity of the radioactive frost boils contained high levels of ^{238}U and ^{226}Ra (Table 4). In general, ^{226}Ra activities in plants were highest at the Main Showing and decreased with the distances from the showing. The highest ^{226}Ra values were found in grasses, sedges, V. uliginosum and willows.

^{226}Ra and ^{137}Cs activities were correlated with those in the top substrate layer. Betula and Ledum showed significant correlations (r= 0.71 and 0.57 respectively) with the substrate for ^{226}Ra, while Dryas was linked with the substrate in terms of ^{137}Cs (r=0.51). It was also seen that the

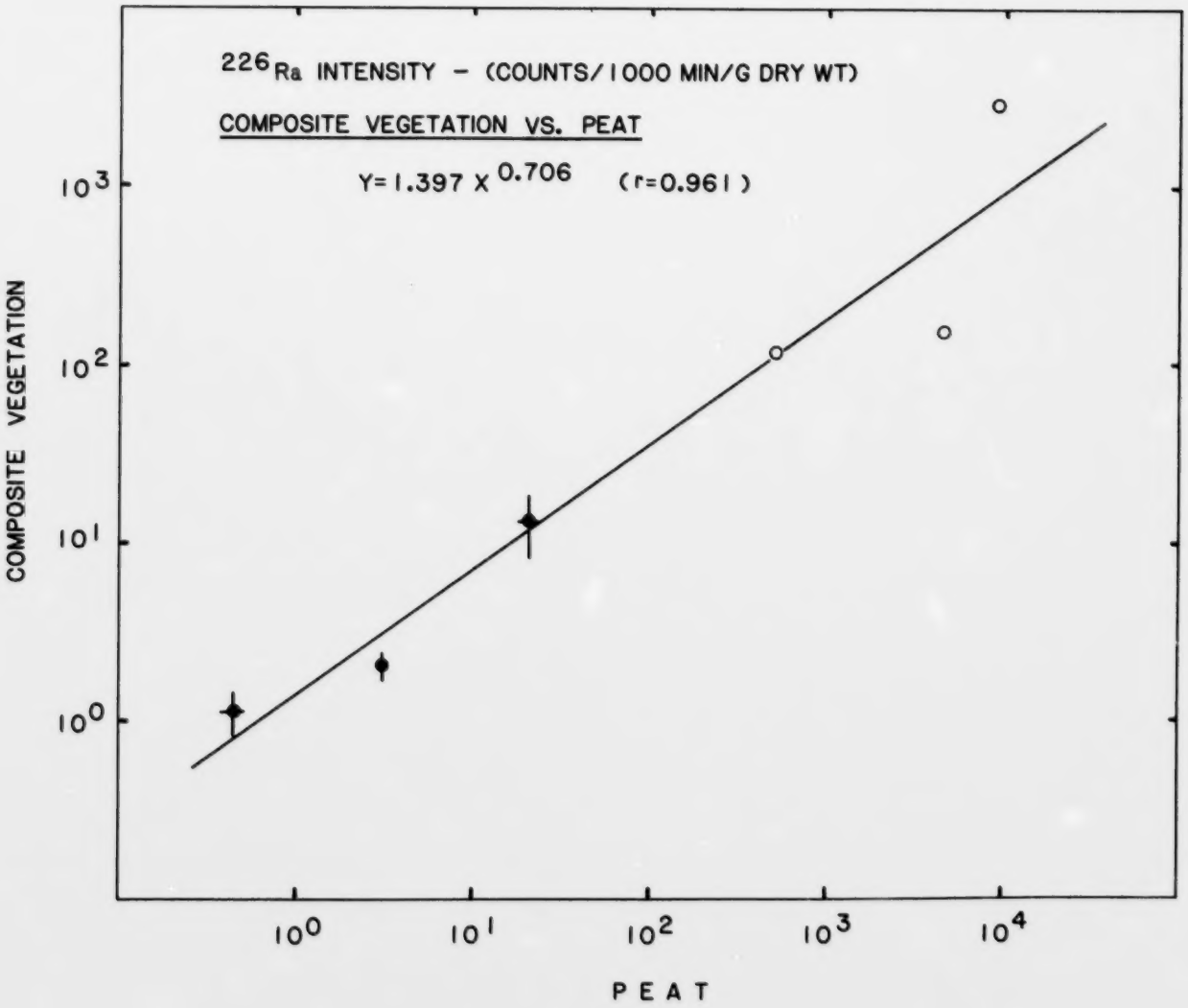

Fig. 9a Relationship between the ^{226}Ra levels of the composite vegetation and peat. (Open circles represent single sample values; closed circles represent average values with the designed interval on the horizontal axis).

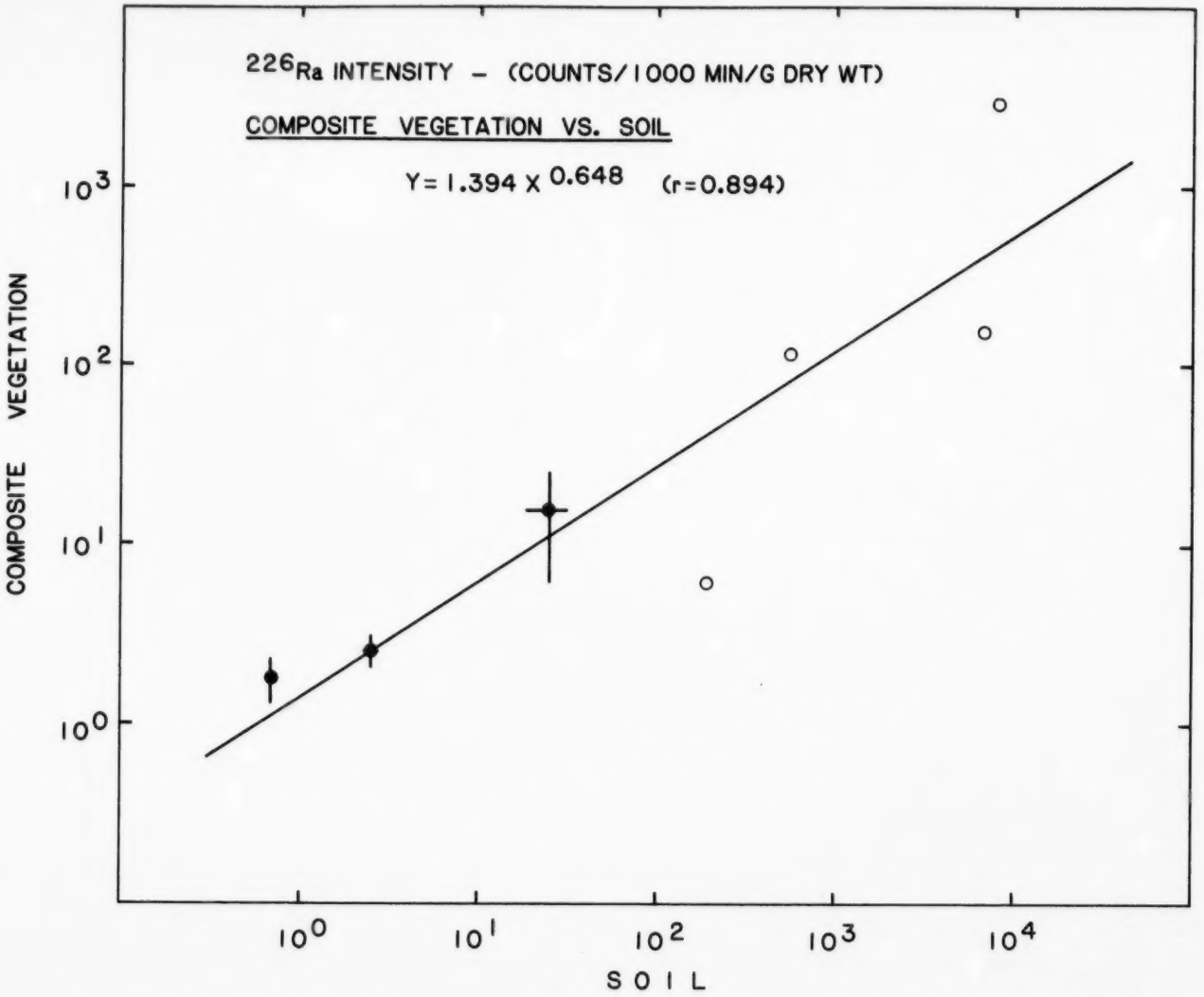

Fig. 9b Relationship between the ^{226}Ra levels of the composite vegetation and soil. (Open circles represent single sample values; closed circles represent average values with the designed interval on the horizontal axis).

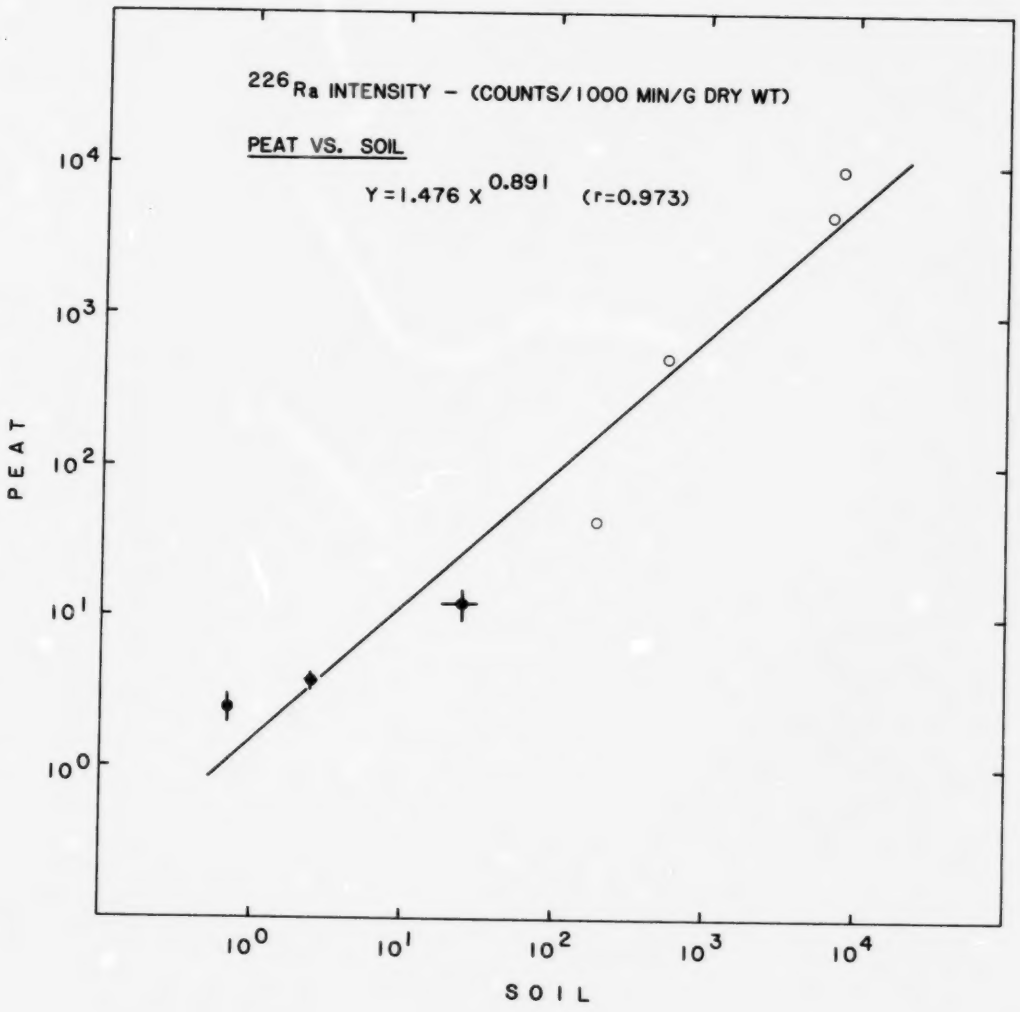

Fig. 9c Relationship between the ^{226}Ra levels of the peat and soil. (Open circles represent single sample values; closed circles represent average values with the designed interval on the horizontal axis).

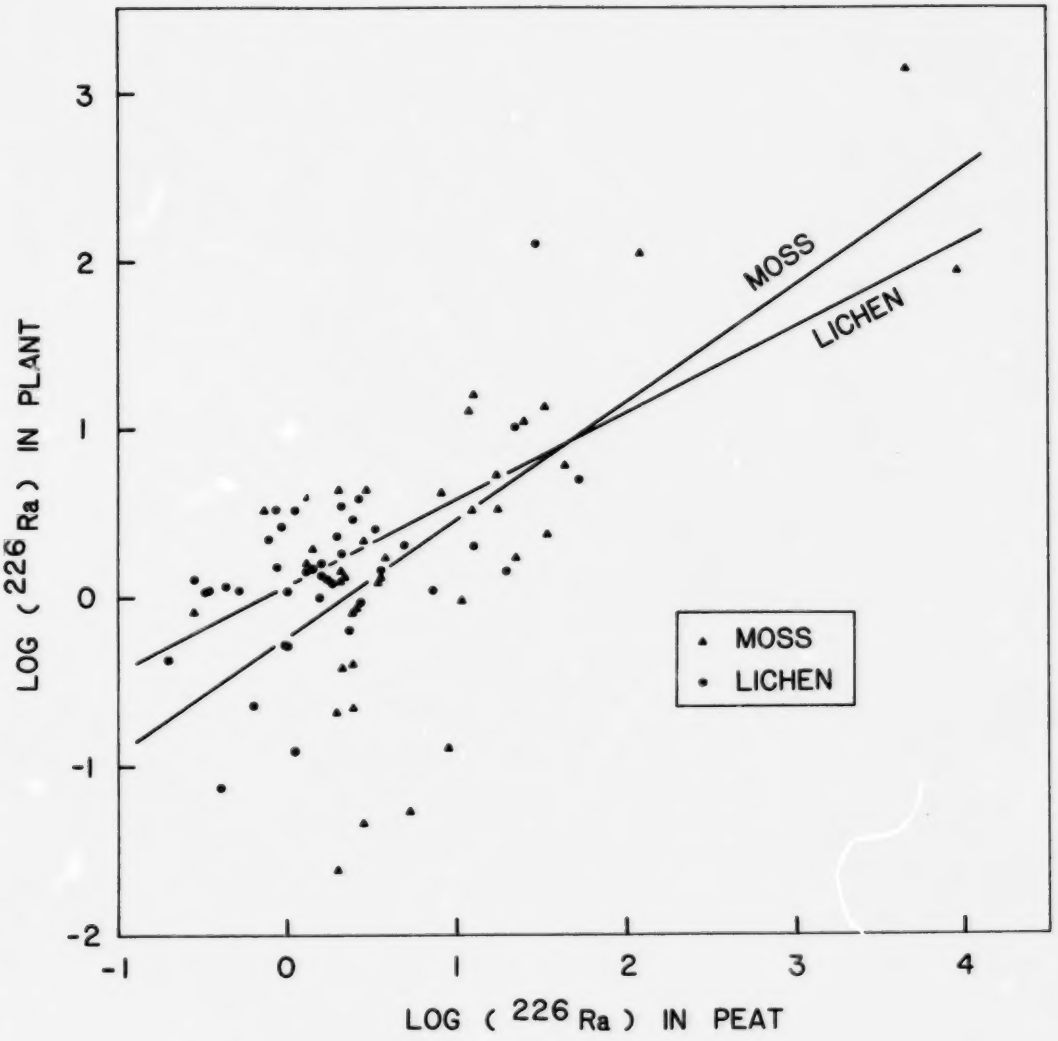

Fig. 9d Scatter diagram of the ^{226}Ra activities of moss and lichen samples versus the activity of the peat. Both regressions are significant at $p<0.001$. The slope of the moss curve is 0.72; that of the lichen curve is 0.52.

^{226}Ra in Betula and Empetrum was significantly associated with substrate ^{137}Cs.

Mosses and Lichens. The relationship of the radionuclide content in the plant tissue and in the substrate was investigated. The slope of the regression curves (Figure 10) of these two growth forms suggest that, under low substrate concentrations, the ^{226}Ra activity in lichens are higher compared to mosses. At areas of higher substrate concentrations, the reverse situation is true. This suggests that mosses are a better indicator of the presence of ^{226}Ra anomaly in the substrate than lichens, as was the case at the Long Gull Main Showing Site (Table 4).

The association between mosses and the substrate through ^{226}Ra was partially borne out by the r-values of these plants correlated with substrate ^{226}Ra (Table 5). Mosses and lichens both reflected the levels of ^{226}Ra in the composite vegetation and the substrates equally well.

The $^{238}U/^{226}Ra$ Ratio in Plants and Substrates

The differential mobilities of ^{238}U and ^{226}Ra under natural conditions are well understood. Differences between their concentrations in a sample may be due to the physical and chemical conditions operating along the route from the original radionuclide source to the sampling point.

The U/Ra ratios for composite vegetation and substrates along the two transects at Lone Gull were determined and are shown in Fig. 11. The maximum at the Main Showing is a strong feature; the Central Showing at 700 m and 900 m E of the Main Showing exhibited a secondary maximum for composite vegetation and substrates. It is interesting to note that the composite vegetation at 30 m E had a U/Ra ratio value of approximately 2.0 while the substrates, particularly the lower layer, had values less than 1.0. For the most part, however, the two layers of substrate displayed similar ratio patterns with values between 0.3 and 0.7.

The composite vegetation along the transect, except in the vicinity of the maxima, generally had values close to 0. This suggests that ^{238}U was almost avoided by plants despite its greater concentration in the substrate. Substantial fluctuations in the ratio were evident in the low-lying areas south and east of the Main Showing as it was also observed in the original radionuclide survey. It appears that secular equilibrium (i.e. activity of ^{238}U/activity of ^{226}Ra =1) only existed in the areas of uranium showing and points of hummocky terrain.

Individual species collected from various localities also contained activities of ^{238}U below the equilibrium condition (i.e. points above the line, Fig. 10). It is evident that all the plant species examined contained levels of ^{226}Ra greater than or equal to equilibrium amounts over the entire range of substrate concentrations. A tendency was observed for the plant and substrate samples to approach the equilibrium condition for activities above 100 pCi/g.

Table 4. Radionuclide activities in plants collected from the three sampling points at the Lone Gull Main Showing area. Mean±SE.

	Main Showing			30 m F			125 m W		
	^{238}U (ppm)	^{226}Ra (pCi/g)	^{137}Cs (pCi/g)	^{238}U (ppm)	^{226}Ra (pCi/g)	^{137}Cs (pCi/g)	^{238}U (ppm)	^{226}Ra (pCi/g)	^{137}Cs (pCi/g)
Lichens	-	60.0±7.2	17.2±1.8		- NP -			- NP -	
Mosses	408	308.3±35.3	8.7±0.9	16000	88.9±10.4	11.3±1.3	31.1	34.3±5.0	4.5±0.5
Grasses	550	180.6±20.8	1.2±0.3	-	3584±408	3.6±0.8	-	140±16	0.3±0.1
Sedges	1190	351.5±40.6	4.2±0.9	298	933±107	1.8±0.5	-	2.3±2.3	2.0±0.4
Salix spp.	71.6	150.3±17.2	1.2±0.3	-	539±61	1.1±0.2	-	120±14	0.4±0.2
Betula glandulosa	-	118.3±13.5	1.3±0.3	-	82.6±9.5	2.9±0.3	26.0	78.5±9.0	0.2±0.1
Oxytropis maydelliana	87.6	107.4±12.6	2.9±0.4		- NP -		-	22.1±3.2	1.0±0.2
Arctostaphylos alpina	-	132.7±15.3	2.8±0.4	-	76.7±9.0	1.8±0.3	33.7	135±15	0.3±0.1
Vaccinium uliginosum	84.0	41.1±5.0	1.9±0.3	-	542±62	3.6±0.0	-	37.9±4.5	0.5±0.1
V. Vitis-idaea	97.0	168.6±19.4	2.0±0.4		- NP -			- NP -	
Cassiope tetragona		- NP -			- NP -		-	6.4±1.5	2.5±0.3
Ledum decumbens	235	198.6±22.6	2.2±0.3		- NP -		-	40.2±5.0	1.1±0.2
Empetrum nigrum	-	66.8±7.7	3.0±0.4	-	40.6±5.0	3.1±0.4	21.6	51.5±6.3	0.9±0.2
Dryas integrifolia		- NP -			- NP -		-	107.7±12.7	1.6±0.2

"-" not determined; - NP - not present

Table 5 . Correlation coefficients of ^{226}Ra and ^{137}Cs levels in lichens and mosses versus that in composite vegetation and the two substrate layers. ()=n. For levels of significance, see Table 1.

		^{226}Ra		^{137}Cs	
		Mosses	Lichens	Mosses	Lichens
Composite vegetation	^{226}Ra	0.987 *** (40)	0.988 *** (40)	-0.162 NS (40)	0.150 NS (40)
	^{137}Cs	-0.262 NS (40)	0.002 NS (40)	0.505 *** (40)	0.447 *** (40)
Top layer substrate	^{226}Ra	0.943 *** (39)	0.447 *** (40)	-0.120 NS (39)	0.187 NS (40)
	^{137}Cs	-0.029 NS (39)	0.643 *** (40)	0.354 ** (39)	-0.029 NS (40)
Second layer substrate	^{226}Ra	0.905 *** (29)	0.965 *** (32)	-0.174 NS (29)	0.194 NS (32)
	^{137}Cs	0.238 NS (29)	0.271 NS (32)	0.324 NS (29)	0.042 NS (32)

Table 6 . Correlation coefficients between ^{238}U and ^{226}Ra in the composite vegetation and the substrates from Lone Gull.

	Pooled data			North transect		
	r	n	P	r	n	P
Composite vegetation	0 887	44	<0.001	0.468	7	NS
Top layer substrate	0.999	40	<0.001	0.636	7	0.1
Second layer substrate	1.0	33	<0.001	0.923	6	<0.001

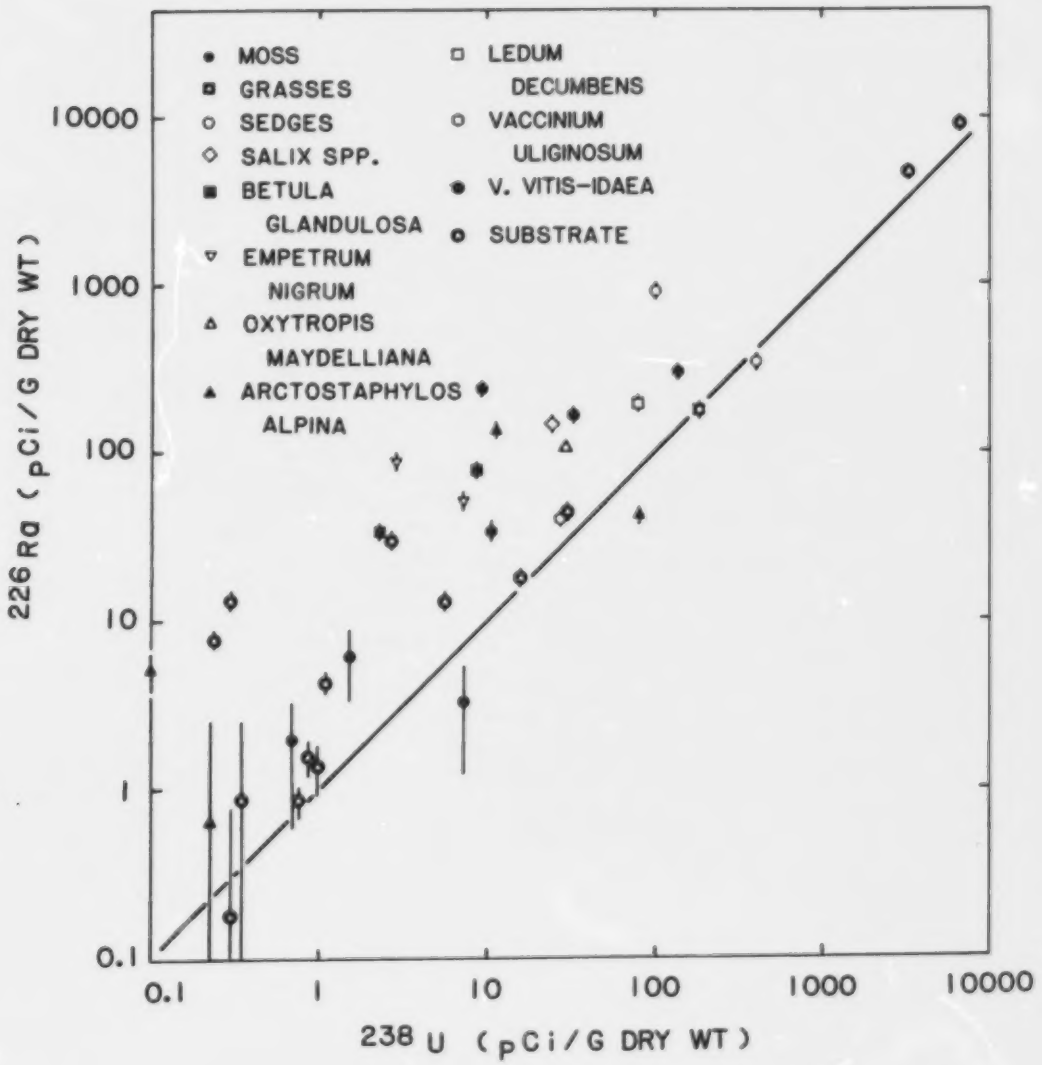

Fig. 10 The relationship between 226Ra and 238U activities in plant species and substrates. Line represents secular equilibrium.

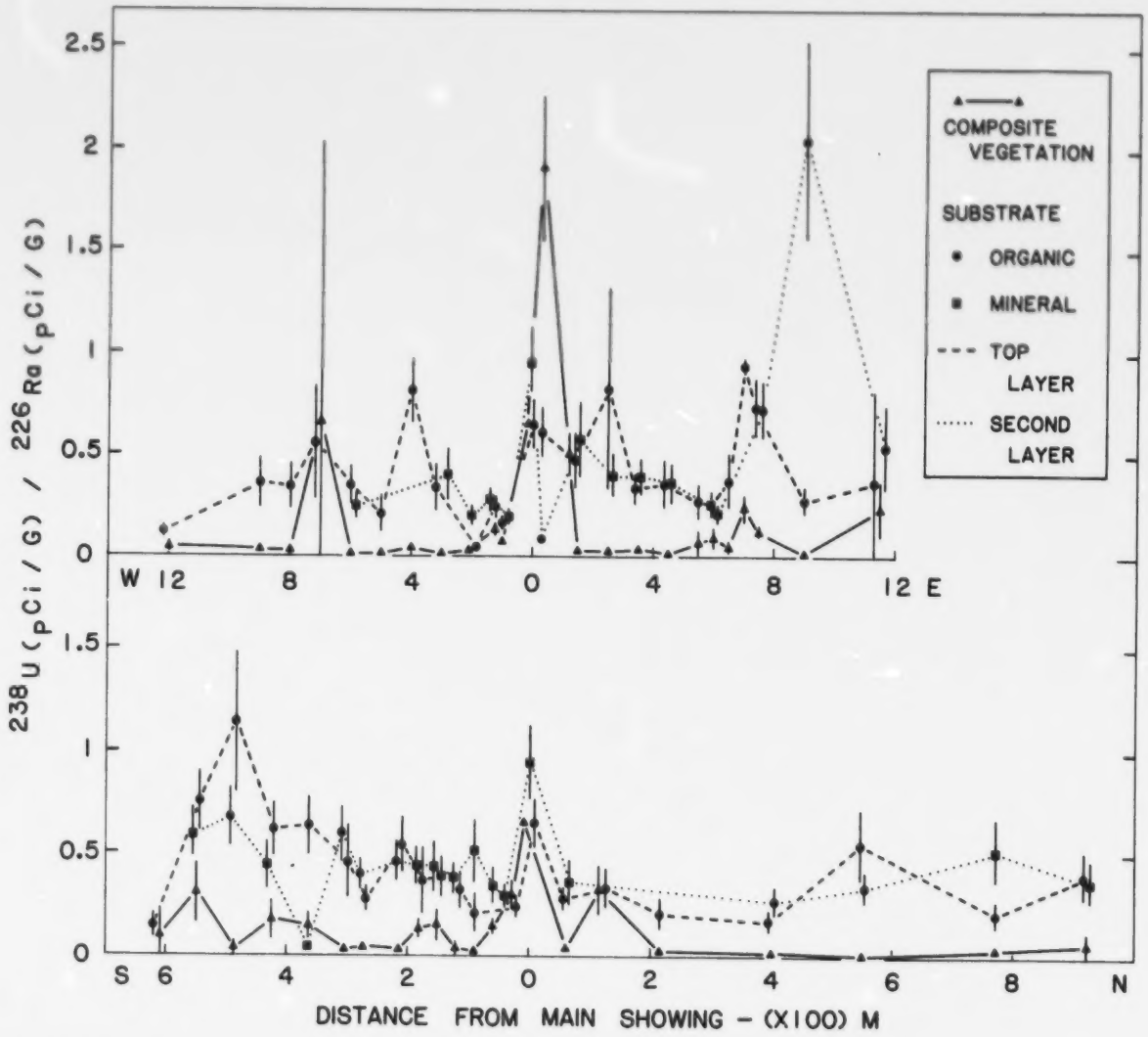

Fig. 11 Profiles of U/Ra values (both converted to pCi/g) in the composite vegetation and the substrates along the two main transects of Lone Gull Camp. Secular equilibrium condition exists when the U/Ra ratio is 1.

DISCUSSION

Uranium Geochemistry

The biotic and abiotic factors in the northern environment influence the dispersion of mineral radionuclides in quite a different fashion than in the temperate regions. Permafrost effectively seals the underlying strata. There is no migration of weathered minerals between the permafrost and the active layer. Thus, any observed geochemical dispersion or translocation occurs solely within the active layer. Uranium radionuclides may be dispersed in the permafrost by means of: 1) the weathering of uranium outcrops; 2) by smearing of the ore body in the past by abraisive glaciers which produced mineralized boulder trains and deposited glacial debris in the direction of ice movement (Gustafsson and Minell 1977). If the mineralized bedrock is present at or near the surface, frost cracking and heaving would bring the weathered particles to the surface, as is the case at the Lone Gull Main Showing in central Keewatin. The shattered bedrock has more surface area for chemical weathering and is likely to produce a more significant dispersion halo down-slope from the showing.

Signs of the Wisconsin Glaciation are still evident. Boulder fields resulting from frost cracking, heaving of the bedrock and mudboils are frequently encountered in the study area. The active layer is between 25-200 cm thick and the permafrost is about 300 m deep. Precipitation (110 days) is relatively abundant with an average of 260 mm per year. This allows soluble and particulate matter to be redistributed on the tundra surface and to be accumulated in depressions. Thus the distribution of the radionuclides of the uranium family in the plants and substrates is closely associated with local topography. The extent of the uranium distribution at the two intensively studied sites, Lone Gull and Nogash, illustrate such a relationship.

Radionuclide Survey of the Intensive and Extensive Sites

Lone Gull Site

The landscape at Lone Gull was generally of a gentle SE aspect with drier conditions prevailing in the northern areas and a hummocky sedge-meadow dominating the southern region. The drainage pattern followed this topographic trend so that the runoff from the uranium mineralizations was collected in the area directly south of the Main Showing. The plant communities were Heath-Moss in the dry-mesic habitat, Low Shrub-Heath in the mesic sites and Sedge-Moss in the meadows. In the mesic and wet habitats, the substrate was highly organic throughout the top few centimeters and it became predominantly mineral below 10 cm with an increase in the fine fractions of silt and clay relative to sand with increasing depth. In the meadows, the thick layer of peat coupled with the reducing environment, made the area south of the Main Showing a suitable sink for transported uranium radionuclides and fallout cesium. At Lone Gull the average ^{226}Ra content in the top substrate layer of the south transect was at least twice that of the east and west transects. The upslope north transect had the lowest substrate ^{226}Ra content. This clearly demonstrates the influence of drainage upon the lateral distribution of ^{226}Ra. Large anomalies in gross gamma radiation at the Main Showing and the Central Zone were first detected using the portable

gamma-ray counter. However, Marmont et al. (1978) have detected an increase of 2-5 times the background radioactivity in areas where granite was present. Therefore, it would be false to ascribe casually gross radiometric readings to the occurrence of uranium. This justifies the need for gamma-ray spectrometric analysis of plant and substrate samples which permits the study of individual surface components (e.g. individual plant species) and substrate layers.

In terms of a vertical distribution, the correlation analysis between the radionuclide burden and the measured edaphic parameters suggests that clay and organic matter were involved in concentrating uranium radionuclides.

The ^{226}Ra burden between the peat and the mineral substrate layers remained the same for the east and west transects but showed a significant drop in the north and south transects. Since no clear differences existed between the E-W and the N-S transects in terms of substrate depth and organic content patterns, the N-S aspect and the associated drainage orientation must be responsible for this phenomenon.

The presence of ^{238}U within the low-lying area south of the Main Showing indicated a significant migration of uranium in the area. Marmont et al. (1978) traced this anomaly 600 m down the gentle slope. Our study detected elevated concentrations of ^{238}U at about 500 m south of the Main Showing. Sheppard and Thibault (1984) and Vaananen (1975) have also shown that, in non-permafrost regions, uranium tends to concentrate in low-lying areas such as bogs and valleys.

At 3 to 13 ppm, the concentration of ^{238}U in the Lone Gull substrates was higher than that found in Saskatchewan of 1-3 ppm (Dunn 1980). In the permafrost region (Hornby Bay, NWT), Hoffman (1983) detected the background level of ^{238}U in the substrate to be 0.5 ppm while 1 to 2 ppm, i.e. 2 to 3 times the background was considered to be the threshold for anomalous values. Other cited values of ^{238}U in soil are 1 ppm (Rose et al. 1979) and 3 ppm in tundra in the USSR (Malyuga 1964 citing Vinogradov 1957).

^{226}Ra activities in the plants and substrates of Lone Gull were higher than those cited by Brooks (1972) (0.02 pCi/g in plant ash and 0.8 pCi/g in soil). Not including the Main Showing, the substrate average at Lone Gull was 12 pCi/g i.e. 15 times the value cited by Brooks (1972). Sheppard and Thibault (1984) calculated that by ashing plant tissue, a 20 to 50-fold increase in non-volatile mineral concentration was achieved. If this factor is accounted for, the Lone Gull average of ^{226}Ra concentration in the vegetation becomes about 7000 times higher than the Brooks (1972) value. This would suggest that the plants in the entire area of Lone Gull contain elevated levels of ^{226}Ra.

^{238}U and ^{226}Ra activities fluctuated in an apparent response to the hummocky terrain. Both uranium and fallout radionuclide concentrations vary from the top of a hummock to the hollow at its base. The hollows were frequently water saturated, and in a reduced state. Dissolved mineralssuch as ^{238}U will precipitate and accumulate more readily under these conditions. ^{226}Ra is more soluble in a reduced environment and consequently should have a wider radius of distribution in the waterlogged

areas. However, the results of this study did not confirm such a pattern. In fact, along the southern transect, ^{226}Ra tended to localize in the surface layer of substrate which suggests that the adsorptive capacity of organic matter plays a significant role in the vertical and lateral translocation of ^{226}Ra. The pattern of ^{238}U distribution at Lone Gull was remarkably similar to that of ^{226}Ra. Local maxima in both nuclides have been found to correspond closely with drainage basins (See figure 2a).

At Lone Gull, the correlation between uranium and ^{226}Ra in the plant and substrate samples were statistically significant without including the Main Showing values (Table 6). The correlation coefficient increased from the plant layer to the mineral layer. This held true even along the northern transect where the levels of these nuclides were lowest. The implication is that, in addition to a common mechanism of lateral distribution, there is a selective factor influencing the fixation of various radionuclides in the substrate.

Surprisingly, at the Main Showing area, ^{226}Ra and ^{137}Cs were significantly correlated in the composite vegetation and the substrates. These radionuclides generally do not correlate, since ^{137}Cs is always concentrated in the surface layer while the pattern for ^{226}Ra was less clearly defined.

At Lone Gull, the main mechanism of mineral dispersion is believed to be the runoff during snowmelt. This assumption is derived from the hydrological study by Woo and Drake (1983) at the Lone Gull site. These workers have documented a large pulse of meltwater in the short period of spring melt (2 weeks) and a pattern of extensive surface flow which is not confined to stream channels. The meltwaters carry soluble and particulate radionuclides down the topographic gradient. Some eolian transport will occur during the summer towards the means of SE by means of the prevailing wind; however, this should not contribute as much to the dispersion pattern because of the limited area of exposed ground surface. Uranium activities in vegetation do not show any strong pattern attributable to wind dispersal. In the southern U.S., the contamination in plants downwind from uranium tailings pile was minor with a detectable dispersal range of 800 m (Marple 1980). On this basis, the wind transport situation at Lone Gull is negligible.

At the Central Zone (750 m E), the mineralization occurs below the shallow overburden. The site showed detectable radioactivity (10 to 100 times weaker than that at the Main Showing, however) even though there were no radioactive frost boils present. A third mineralization site (Eastern Zone) 1400 m SE of the Main Showing failed to present a radiometric or geochemical anomaly. Presence of an overburden up to 15 m thick (W. Hilger, personal communication) prevented the detection of the mineralization at the surface.

To summarize, the plants and substrates at the Main Showing and the Central Zone contained elevated levels of the uranium family radionuclides, but their activities are localized to an area not greater than 100 m in radius about the showing. The composite vegetation and the substrate at Lone Gull revealed a detectable dispersion pattern of ^{238}U and ^{226}Ra. The average levels of these nuclides were highest in the south and lowest in

the north. The ^{137}Cs in the composite vegetation showed a remarkable consistency throughout the Lone Gull area. ^{137}Cs in the substrate fell rapidly with increasing depth; its distribution showed some evidence of association with the local watershed.

Nogash Site

The main uranium mineralization zone lies within a drainage basin under 20 m of glacial overburden.

The standing crop in the two intensively studied localities showed that Lone Gull had an average of 1204 g dry wt per m^2 while at Nogash it was 1444 g (stands with spruce were not included). However the ^{137}Cs level (8 pCi/g) was essentially the same as at Lone Gull while the substrate ^{137}Cs was only about half of that at Lone Gull.

At Nogash, the main uranium mineralization is locked within the permafrost and permitted little migration of radionuclides to the surface. However, the permafrost table is most probably absent under Lac Cinquante (Levinson 1974). Hence, the mineralization zone can become part of the region of groundwater flow system and it is likely that radionuclides migrate upward to the surface from the mineralized groundwater. However, little radioactivity was detected in the sediment-rich substrate.

^{226}Ra activity in the vegetation from the west shore of the lake was one of the highest at the Nogash site. Since some drilling has occurred up-slope, the surface may have been contaminated by the down-wash of drilling discharge. The highest ^{226}Ra readings were only 2 to 3 times the local average of 1.6 pCi/g, and were found both on the mineralization zone and well away from it.

^{238}U concentrations were not determined for samples collected from the Nogash site, since these can be calculated from the $^{226}Ra/^{238}U$ ratio derived at Lone Gull.

The discrete nature of "gash" veins on the outcrops limits the weathering and leaching of radioactive material from them. These veins are believed to be inadequate for the creation of a significant dispersion halo as demonstrated by the Nogash area, known as "Magnum Mountain". Scintillometer readings of 400,000 + cpm were measured at the "gash" vein, which is at the base of the outcrop but about 10 m away. No anomaly was detected in the substrates.

Terrain disturbance and signs of drilling were encountered near several sampling points. Dyke (1981, personal communication) observed levels of ^{238}U higher than the background in the peat of the main drainage basin (south of the mineralization zone), mainly in areas of track vehicle compaction. However, it appears that contamination from drilling was not a significant factor in producing the radionuclide burden of Nogash. Terrain disturbance, however, is a more serious concern as deep ruts have been created in the depressions over the entire Nogash area. The tracks have removed the vegetation cover and churned up the substantial peat layer. Runoff erosion could cause further deterioration of the situation.

To sum up, the Nogash intensively studied site was characterized by very low ^{226}Ra activities (and probably low ^{238}U concentrations) in vegetation and substrates over the mineralization zone and in the surrounding environment. There are scattered glacially-transported radioactive boulders and shallowly buried uranium veins on local basaltic outcrops. These do not appear to contribute to the formation of detectable patterns of uranium dispersion. The pattern of the ^{137}Cs distribution does not appear to be different from that of the Lone Gull site either laterally or vertically.

Extensive Sites

The region of Keewatin within the study area is richly mineralized with uranium. However, economic deposits such as those at Lone Gull seem to be rather rare. Most uranium mineralization occurs in the form of diffused zones which are usually detectable as "geochemical highs" but without a discrete "hotspot". Kazan Falls South and Nutarawit Lake sites are examples of such "geochemical highs". Some areas greater than 300 m in length, exhibit ^{226}Ra activities higher than background.

Christopher Island contains a large area (> 300 m in length) of elevated radioactivity which is easily detectable with the portable scintillometer. No corresponding increase of ^{226}Ra activity in the surface samples was observed, however. Only the mineral layer of the wet habitat showed 10 times the background value.

Two highly radioactive pits reminiscent of the Lone Gull Main Showing were excavated from an area of frost-heaved bedrock at the Forde Lake site. The vegetation and substrate showed ^{226}Ra activities 10-100 times the background. Individual plant species collected from the mineralization area also contain rather high amounts of ^{226}Ra.

Drilling has taken place in Kazan Falls South (Miller 1982, personal communication). ^{226}Ra activities in the substrate were 10 to 100 times the background, and increased with depth. The level of gross radioactivity was consistently high, even 150 m from the mineralized zone.

^{226}Ra activities in the vegetation at Arbitrary Sites were very much below 1±0.4 pCi/g or 68% below the detection limit. Interestingly, the ^{226}Ra activity in the vegetation of 42% of the uranium mineralized sites averaged 7±4 pCi/g, which is comparable with the arbitrary areas of unknown mineralization. Greater contrast between mineralized and Arbitrary Sites was evident in the substrate levels. At the mineralized sites, the mean ^{226}Ra activity was 10 pCi/g near the surface and 21 pCi/g in the lower substrate.

The level of ^{137}Cs in the composite vegetation of the Extensive Sites ranged between 3 (Forde Lake) and 16 pCi/g (Nutarawit Lake) with an average of 7.5 pCi/g. This average was 5% lower than that obtained from Lone Gull and Nogash. At Nutarawit, there was a 100% cover of Sphagnum moss; Forde Lake, on the other hand, had 100% coverage of Eriophorum and Carex but little moss. Therefore, one can conclude that retention of fallout cesium in vegetation is very much species-standing crop dependent.

To summarize the background levels of ^{226}Ra in the vegetation and substrate of the Keewatin region was less than 1 pCi/g. At mineralized sites, ^{226}Ra activities were higher; composite vegetation was 7 pCi/g while 10-20 pCi/g was present in the substrate. No significant difference was evident in the levels of ^{137}Cs between Extensive and Intensive Sites.

Factors Affecting the Distribution of Radionuclides

In the Keewatin region the tundra is water saturated during the snowmelt period. Woo and Drake (1983) have noted that the flooding of peat (wet) sites lasted about 12 days at Lone Gull. The spring melt, therefore, is believed to be the most important mechanism for the lateral distribution of uranium and fallout radionuclides in the tundra environment. The deeper, frozen substrate should neither gain nor lose mineral materials during this period. Peat and mat-forming plants such as moss take part in the absorption and adsorption of soluble and particulate matter carried by the meltwater. Based on their lichen study at Lone Gull, Kershaw et al. (1983) have concluded that significant distributional patterns of uranium, iron, titanium and ^{137}Cs were closely associated with the Main Showing. They suggested that the area of radioactive frost boils is the source of the exponentially decreasing patterns of these metals through airborne particulate deposition on lichens. However, some results presented in their study do not conform to this assumption. Thus, the elevated levels in lichens at distances exceeding 2 km seem rather unlikely, if the only source of airborne particulates as the Main Showing. From the information gathered in our study, it is concluded that a variety of factors affect the distribution and that radionuclide dispersion occurs mainly through water transport and much less by means of the wind in areas with full vegetation cover.

The tetravalent uranium (U^{4+}) (under reducing conditions) has a low solubility and is relatively immobile, being strongly adsorbed to solids. The hexavalent state (U^{6+}) (under oxidizing conditions) is highly mobile and can be extensively dispersed.

Ra^{2+} is water soluble in the form of bicarbonates and chlorides but it precipitates in sulphate form. Its mobility in a reducing environment is high but it is relatively immobile in oxidizing conditions.

^{137}Cs has a low mobility since it adsorbs strongly to soil and plant fractions. It may be displaced by potassium which is, however, in a short supply in tundra environment itself (Davis 1963). From the above, it is expected that ^{238}U ions would be distributed over a wider area than ^{226}Ra and ^{137}Cs. However, this pattern could change if the radionuclides were adsorbed onto organic matter or clay particles, to which both ^{238}U and ^{226}Ra are known to adsorb readily. In such a situation the patterns of lateral distribution of these two radionuclides may not be significantly different. ^{137}Cs is also strongly adsorbed to soil colloids, and it is highly localized in the upper region of the substrate without exception.

The distribution of substrate constituents such as organic matter, silts and clays, plays an important role in the pattern of radionuclide concentration (e.g. Shilts 1972, 1977). Both ^{226}Ra and ^{137}Cs were found to correlate significantly with substrate texture at all sites. The

concentration of uranium in clay can be 10-100x that in coarser fraction (DiLabio 1979) and the inclusion of the predominantly quartz and feldspar in silt and sand fractions only serve to dilute the Uranium concentration in the sample (Steenfelt et al. 1975; Klassen and Shilts 1977).

Although soil pH and Eh (redox potential) can influence the solubility of cations and their dispersion pattern, these factors did not appear important in this study. No significant relationship was found between pH (within the range of 3.7-6.5) and radionuclide concentrations. Eh was not measured but it is assumed that most of the wet sites were saturated with water, thus causing substrate conditions of a reducing nature.

The Association of Uranium and Fallout Radionuclides Between Plants and the Substrate

The Composite Vegetation

The composite vegetation showed a significant correlation with the substrate across the whole range of substrate activities (1-10,000 pCi/g) although the wide variety of communities contributed to some fluctuation in the ^{226}Ra activities (Fig. 9). It is evident that the mixed (composite) plant samples are rather sensitive to changes in the ^{226}Ra concentrations in the substrate, and a reasonable assessment of the surface contamination may be made through the analysis of the composite vegetation. Mosses and lichens tend to accumulate even more ^{226}Ra (as well as ^{137}Cs) than vascular species.

However, it is difficult to differentiate between external contamination and genuine uptake, particularly in evergreen species such as Vaccinium Vitis-idaea and Ledum decumbens. From the positive vegetation-substrate correlation at Lone Gull (Fig. 9) it follows that aerial contamination can not be a significant factor.

In the light of the above discussion, it is clear that in the District of Keewatin plant biogeochemistry can not be superior to substrate geochemistry for the purpose of indicating uranium mineralization. That is, the composite vegetation can not reveal areas of elevated uranium content that are not even more reliably detectable through the substrate.

Low concentrations of ^{238}U were measured in plant species using the delayed neutron activation method. The average background level of ^{238}U in plant species from Baker Lake North and Kaminuriak was 0.15 ppm while the ^{226}Ra concentrations in most sites was less than 0.1 pCi/g. Published results of background levels of uranium radionuclides were similar to the findings of this study (cf. Mahon (1982)); Kljaic et al. (1982)). At localities where uranium mineralization occurs, the variation in uranium concentration in plants can be quite large.

Mosses and Lichens

Mosses have been found to reflect uranium mineralization better than all the other species examined. For example, the ^{238}U concentration in moss at the Lone Gull Main Showing was 408 ppm and 16,000 ppm just 30 m downslope from it; background values are less than 1 ppm. Bryophytes have

shown better correlations with the ^{226}Ra (and ^{137}Cs) concentrations of the substrate than lichens have (Fig. 9). They also contain greater amounts of radionuclides than lichens from the same substrate, which further endorses their effectiveness as biogeochemical indicators. Moss is more abundant in wet depressions and more prone to be flooded during spring runoff. Despite the established use of lichens as an atmospheric quality monitor (Nieboer and Richardson 1981), mosses appear to be superior as indicators of elements originating in the ground. Mosses also act as a trap for airborne ^{137}Cs because old dead parts of this plant remain arranged in the same fashion as in cushion plants such as Dryas integrifolia (Svoboda and Taylor 1979).

Individual Plant Species

At Lone Gull, the plants showed increased levels of uranium radionuclides acquired either through intake or external adherence. Although all plant materials was carefully washed 3 times to remove attached particles, a small undetermined fraction must have remained on the tissue. Species with fine roots or those which form dense mats, such as grasses and mosses, showed the highest degree of "contamination" by adherence.

At Kazan Falls South, Kazan River I and Kazan River II this study revealed that V. uliginosum, B. glandulosa and E. nigrum had the highest ^{238}U and ^{226}Ra content while Salix contained little ^{226}Ra. These species, therefore, can be considered as good potential indicators of uranium. The uranium content of V. uliginosum leaves has been found to correlate significantly with the substrate levels in Keewatin (DiLabio and Rencz 1980). However, this plant showed less sensitivity to radionuclides than the mosses taken from the same samples. It is important to note that both ^{238}U and ^{226}Ra radionuclides were present in elevated amounts in plants collected from showing sites.

Plant-Substrate Relationships

A great deal of work has been done by Soviet scientists (Malyuga 1964; Kovalevskii 1979) and other workers (see Brooks 1972) on the nature of plant uptake of uranium and other elements with economic importance.

Kovalevskii (1979) found that the accumulation in plants does not normally exceed, 2-3X the background level of the substrate. The results of our study, however, show that most arctic plants had lower ^{238}U and ^{226}Ra activities than the substrate.

In northern Saskatchewan, ^{238}U concentrations of 100X background have been detected in black spruce twigs; twig samples contain as much as 400X the soil concentration (Dunn 1981, 1982). Clearly, plants in northern, but non-permafrost regions are capable of concentrating uranium to a greater extent than those from regions underlain by permafrost.

Plants have no physiological barrier to radium and other alkaline earth elements while the uranium uptake is limited (Kalin and Sharma 1982). However, our study did not reveal any significant differences in the concentration of these two elements in the plants analysed.

Of the ten common vascular species examined, Betula glandulosa and Ledum decumbens have shown significant correlation of ^{226}Ra concentrations with the substrate while Vaccinium uliginosum was not statistically significant. The concentrating factor of ^{226}Ra in Cassiope was found to increase with increasing substrate levels but the observed levels did not exceed 4 pCi/g. It must be pointed out that Cassiope was not present in samples from the vicinity of uranium outcrops so that its true capacity to concentrate ^{226}Ra could not be established.

Plant Growth and Radiation Exposure

A unique and theoretically possible means of mineral prospecting for uranium is the use of unusual plant growth induced by radiation. Only one example of a possible growth anomaly was found. A L. decumbens twig collected from a Kazan River II showing site bore a number of enlarged leaves proximal to normal leaves. Some Vaccinium Vitis-idaea leaves collected from this site also appeared larger than normal. The average gamma-ray dose at the collection site was 0.04 mRoentgen/hr but radioative boulders with emission rates exceeding 1 mRoentgen/hr were scattered in the area. A similar rate of exposure exists at the Lone Gull Main Showing, but no obvious aberrations in growth form were observed. McInnes (1981 personal communication) described Pedicularis as having subtle abnormalities in the flower morphology. These plants were said to have been growing in a "hot" sedge meadow near Nogash Camp. Our attempts to locate the "hot sedge meadow" were unsuccessful.

CONCLUSIONS AND RECOMMENDATIONS

The present inventory of radionuclides in plants, organic matter and mineral substrates establishes a baseline for the monitoring of the environment in the event that mining and milling activities occur in the future. It also reveals the importance of factors such as substrate and habitat conditions in the vertical (from the plants to the mineral substrate) and lateral (from the source to the surrounding area) distribution of radionuclides.

The dispersal of radionuclides in mineralized areas of the Keewatin region is strongly influenced by local topography. During the spring runoff radionuclides are transported down-drainage to low-lying areas where they are deposited and often concentrated.

In terms of an environmental monitoring program at a given site, it is recommended that, the local watershed be mapped first; the area which receives the runoff from the radioactive source (natural or man-made) should then be systematically sampled. The surface organic layer, is a good medium to sample and should give a representative picture of the radionuclide secondary distribution near the tundra ground surface.

Given the limited extent of natural uranium radionuclide dispersion (to 600 m) from the source, a sampling grid of 100 m intervals extending to 2 km from the source should provide an adequate monitoring scheme. Although lake and stream waters were not sampled in the present study, they are effective in transporting and storing natural radionuclides and must be taken in to consideration in any monitoring program.

This study has shown that the Lone Gull mineralization area has slightly above normal levels of uranium radionuclide concentration at 5 pCi/g in the composite vegetation and 12 pCi/g in the substrate. These averages do not include the higher values of the Main Showing area. Although only the track vehicles carrying the drill rig were permitted to traverse the tundra, they have left considerable damage to the landscape. Also extensive drilling took place in 1982 and some of the discharged drill mud had high levels of ^{226}Ra (2.3 mCi/g). In view of its large uranium ore body the Lone Gull mineralization site has a great potential for environmental damage should a mining operation commence. Already the physical disturbance of the terrain and the radionuclide contamination due to drill and mud spills caused considerable site deterioration. This may get worse if proper corrective measures are not implemented.

At the Nogash site the mineralization zones were either buried under thick glacial overburden or are fine-veined so that the activity due to the dispersion of radionuclides does not exceed background values. The local drainage pattern was clearly defined so that any down slope transportation could be readily detected in the drainage basins or in the lakes into which the basins drained. However, with active drilling in place, it is conceivable that elevated concentrations of uranium will occur and accumulate in the ruts formed by track vehicles.

Individual plant species vary in the levels of uranium radionuclides they contain; these are closely associated with the burden in the substrate. Some of the plants, especially heath species should be investigated further as potential uranium indicators. Such a study could be useful in the monitoring program of environmental contamination rather than as a tool for uranium exploration. For the prospecting for uranium, it seems that biogeochemistry is not feasible in the permafrost region for the following reasons: i) arctic plants have shallow roots which prevent them from reaching deep below the surface such as trees do in the boreal region; ii) since arctic vascular plants take up uranium radionuclides in direct proportion to the substrate concentrations (i.e. without evidence of bioaccumulation) it may be easier to analyse the substrate for its higher specific activity. The mineralization zone should be more easily detectable with a scintillometer without the laborious procedure of sample analysis.

Since lichens possess extensive and complex surfaces they contain higher amounts of surface transported ^{226}Ra than vascular plants do. Moss cushions can externally trap particulate matter more effectively than vascular plants, also. Thus in the case of water- and wind-transported particulates or soluble ions, mosses and lichens seem to be most efficient in responding to the influx of transported radionuclides. Therefore, mosses and lichens should be included among plants selected in a monitoring program.

In the Central Keewatin the background level of ^{238}U has been established at 0.2 pCi/g in the plants and 0.5 pCi/g in the substrate. The ^{226}Ra concentration in the plants was very low, in most samples less than 1 pCi/g (the detection limit of the Ge[Li] counting system used in this study). The substrate ^{226}Ra was determined to be 1.5 pCi/g. It is therefore suggested that, for central Keewatin, ^{238}U concentrations > 3 ppm

in the plants and > 5 ppm in the substrate (^{226}Ra levels > 3 pCi/g in the plants and > 9 pCi/g in the substrate) may be considered anomalous and indicative of the presence of uranium mineralization.

In terms of edaphic factors, organic matter and clay content were found to be important factors in the distribution of natural and fallout radionuclides in the study area. ^{238}U and ^{226}Ra were both well represented in the substrate which could suggest the approximately equal binding of these radionuclides to organics and clays. ^{137}Cs was concentrated primarily near and at the ground surface.

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Appendix 1. Plant species list.

Nomenclature Follows Porsild and Cody 1980.

Collection made by T. Lei in 1981 and 1982 in the District of Keewatin. Identification of Carex species and confirmation of others by P.W. Ball. The collection was deposited in the University of Toronto herbarium at Erindale College.

The numbers correspond to site of collection, as follows:

1 - Lone Gull
2 - Nogash
3 - Baker Lake
4 - Grant Lake
5 - Kazan Falls South
6 - Kazan River I
7 - Rankin Inlet

The location of the sites are listed in Figure 1b.

	1	2	3	4	5	6	7
POLYPODIACEAE							
Dryopteris fragrans (L.) Schott.	*		*				
Woodsia ilvensis (L.) R.Br.			*				
EQUISETACEAE							
Equisetum arvense L.	*						
LYCOPODIACEAE							
Lycopodium annotinum L.	*						
PINACEAE							
Picea glauca (Moench) Voss var. *Albertiana* (S. Brown) Sarg.		*					
GRAMINAE							
Arctagrostis latifolia (R. Br.) Griseb.	*						
Festuca brachyphylla Schultes	*						
Hierochloe alpina (Sw.) R. & S.	*						
Poa arctica R. Br. ssp. *arctica*	*						
P. glauca M. Vahl.	*						
CYPERACEAE							
Carex aquatilis Wahlenb. ssp. *stans* (Drej.) Boott	*						
C. atrofusca Schk.	*	*					
C. Bigelowii Torr.				*			
C. capillaris L.	*	*					
C. chordorrhiza L.f.				*			
C. media R. Br.	*						
C. misandra R. Br.	*						
C. nardina Fr.				*			
C. rariflora (Wahlenb.) Sm.	*	*					

Appendix 2 (Cont.)

	1	2	3	4	5	6	7
Carex rotundata Wahlenb.	*	*					
C. saxatilis L. var. *rhomalea* Fern.	*						
C. scirpoidea Michx.	*	*				*	
Eriophorum angustifolium Honck.		*	*		*		
E. vaginatum L. ssp. *spissum*	*				*		
Kobresia myosuroides (Vill.) Fiori & Paol.	*						
K. simpliciuscula (Wahlenb.) Mack.	*						
Scirpus caespitosus L. ssp. *austriacus* (Pallas) Asch & Graeb.	*				*		
JUNCACEAE							
Juncus albescens (Lange) Fern.	*						
J. castaneus Smith	*						
Luzula confusa Lindebl.	*			*			
L. nivalis (Laest.) Beurl.	*						
L. Wahlenbergii Rupr.	*	*					
LILIACEAE							
Tofieldia coccinea Richards.				*			
T. pusilla (Michx.) Pers.	*	*		*			
ORCHIDACEAE							
Habenaria obtusata (Pursh) Richards.		*					
SALICACEAE							
Salix arctica Pall.	*			*			
S. arctophila Cockerell		*			*		
S. brachycarpa Nutt.							
S. Chamissonis Anderss.					*		
S. fuscescens Anderss.						*	
S. herbacea L.	*						
S. planifolia Pursh	*						
S. reticulata L.	*	*					

Appendix 2 (Cont.)

	1	2	3	4	5	6	7
BETULACEAE							
Betula glandulosa Michx.	*			*		*	
POLYGONACEAE							
Oxyria digyna (L.) Hill	*						
Polygonum viviparum L.	*						
CARYOPHYLLACEAE							
Cerastium alpinum L.	*		*				
Meladrium apetalum ssp. *arcticum* (Fr.) Hult.	*						*
Sagina caespitosa (J. Vahl.) Lge.	*						
Silene acaulis L. ssp. *acaulis*	*	*					
Stellaria monantha Hult.	*						
RANUNCULACEAE							
Anemone parviflora Michx.		*	*				
A. Richardsonii Hook.			*				
Ranuculus lapponicus L.	*						
R. pygmaeus Wahlenb.	*						
PAPAVERACEAE							
Papaver radicatum Rottb.	*						
CRUCIFERAE							
Arabis arenicola (Richards.) Gel.				*			
Draba glabella Pursh	*		*				
D. lactea Adams	*	*	*	*			
D. nivalis Liljebl.		*	*				
D. pilosa Adams		*	*				
Eutrema Edwardsii R. Br.	*	*					
Cardamine bellidifolia L.	*			*			
C. digitata Richards.	*	*	*				
C. pratensis L.	*						*

Appendix 2 (Cont.)

	1	2	3	4	5	6	7
ERICACEAE							
Andromeda polifolia L.				*			
Arctostaphylos alpina (L.) Spreng.	*			*			
A. rubra (Rehd. & Wils.) Fern.		*					
Cassiope hypnoides (L.) D. Don	*						
C. tetragona (L.) D. Don ssp. *tetragona*	*		*		*		
Ledum decumbens (Ait.) Lodd.	*		*	*		*	
Loiseleuria procumbens (L.) Desv.			*		*		
Phyllodoce coerulea (L.) Bab.	*						
Rhododendron lapponicum (L.) Wahlenb.			*				
Vaccinium uliginosum L.	*					*	
V. Vitis-idaea L. var. *minus* Lodd.				*		*	
DIAPENSIACEAE							
Diapensia lapponica L.	*						
PRIMULACEAE							
Primula egaliksensis Wormsk.							*
PLUMBAGINACEAE							
Armeria maritima (Mill.) Willd. ssp. *labradorica* (Wallr.) Hult.	*		*				
GENTIANACEAE							
Gentiana tenella Rottb.							*
SCROPHULARIACEAE							
Castilleja elegans (Ostenf.) Malte	*						*
Pedicularis hirsuta L.		*					
P. flammea L.			*				
P. labradorica Wirsing		*		*			
P. lanata Cham. & Schlecht.			*				
P. lapponica L.	*	*	*				
CAMPANULACEAE							
Campanula uniflora L.	*						*

Appendix 2 (Cont.)

COMPOSITAE	1	2	3	4	5	6	7
Antennaria angustata Greene	*		*				
A. Ekmaniana Porsild		*					
A. nitida Greene				*			
Arnica alpina (L.) Olin ssp. *angustifolia* (J. Vahl) Maguire	*	*					
Artemisia borealis Pall.	*			*			
Chrysanthemum arcticum L.							*
Erigeron humilis Grah.	*	*					
Petasites sagittatus (Banks) A. Gray		*					
Saussurea angustifolia (Willd.) DC. var. *angustifolia*	*						
Senecio congestus (R. Br.) DC.		*		*			*
Taraxacum hyperboreum Dahlst.	*	*					